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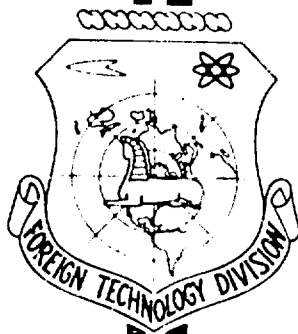
STUDY OF FRICTION OF POLYAMIDES ON STEEL

By

V. P. Mitrovich

FOREIGN TECHNOLOGY DIVISION

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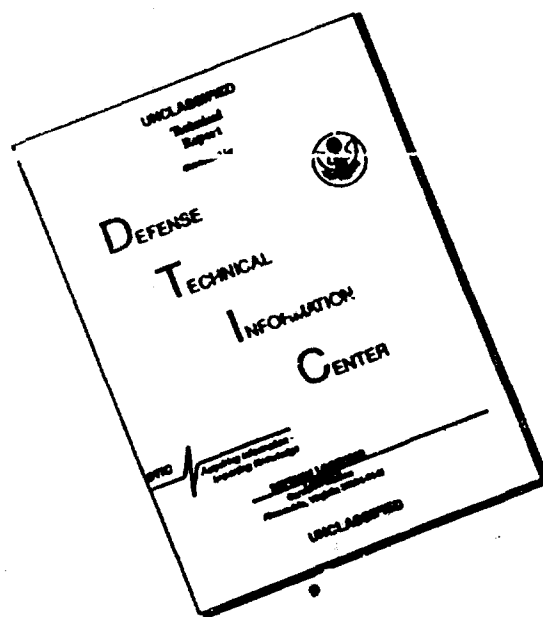
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STUDY OF FRICTION OF POLYAMIDES ON STEEL

BY: V. P. Mitrovich

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PREFACE

The polyamide group comprises plastics with good antifrictional properties. The literature gives examples of the successful use of plastic bearings, and indicates the conditions made necessary by the use of this material for the design of the part. There are still, however, few data on the causes that limit their operating conditions. Elucidation of these causes requires laboratory studies

In connection with the study of the antifrictional properties of plastics at the Institute of Machine Technology, V. P. Mitrovich made an experimental study of the friction of polyamides, and found the factors determining the extreme conditions

of possible operation of polyamides in friction on steel, and tested bearings of capron in the mechanisms of metal-cutting machine-tools.

For laboratory experiments the author developed a number of instruments and devices which are of interest.

This book gives the principal results of laboratory tests conducted at the laboratory of wear-resistance of the Institute of Machine Technology and in the Experimental Research Institute for Machine Tools.

M. Krushchov

INTRODUCTION

The experience in the use of synthetic materials that has accumulated up to now convincingly shows that the use of plastics in machine building can yield an immense economic and technological advantages.

If many articles are made of plastics instead of metals, the labor cost and production cost is sharply decreased, and the scarce nonferrous metals are saved.

One of the promising applications of plastics is their use as slide bearing material. The first materials of this type were rubber, textolite and wood waste plastics with phenolformaldehyde resins as binders. Later, bearing materials were made from polyamides, polytetrafluoroethylene, epoxy resins, etc.

The polyamides today occupy a special position among the plastics used as slide bearing materials.

Their most important feature is high wear resistance. Under certain conditions they withstand loads and sliding speeds as well as babbits and bronzes.

Substantial advantages of polyamides are the high efficiency of manufacture into an article, the possible use in the form of thin-walled bushings and inserts, foil and thin layers ($\sim^{0-2}$ mm) applied to a metal base by gas-flame or vortex spraying.

Successful tests of polyamides used in friction units of various machines and mechanisms have been reported.

Besides their favorable features, the polyamides also have faults, similar to those of certain other plastics: high thermal expansion, power to absorb moisture, relaxation character of the processes during deformation, and tendency under certain conditions to flow under load, leading to dimensional instability of the articles, the need for higher clearances, and the limitation of the upper load limits.

Still more substantial shortcomings are the low heat resistance and the low thermal conductivity.

In connection with the relatively high coefficients of friction, the last two properties may be particularly acute: the antifrictional properties are impaired and the serviceability of polyamide bearings may bo sharply impaired.

One of the conditions of lack of friction with metals /1/ is that the anti-friction properties under conditions of friction with boundary lubrication corresponds to those properties of the bearing material which assure a lower temperature on the friction surfaces, protecting the boundary lubricant layer from destruction. This condition is correct not only for metals but also for plastics, where the limitation of the temperatures is particularly important.

One of the methods of improving serviceability and lowering the temperature of plastic bearings is to improve heat removal, which can be accomplished by design measures or by improving lubrication.

But there is also another way, to improve the antifrictional properties of the plastics themselves. To take this way one must know the specific features of plastics and the primary factors determining their friction.

In spite of the large number of research projects devoted to the study of the physical properties of plastics, no fundamental criterion has yet been found for establishing with sufficient definiteness, the possibility of using a polymer in some specific bearing.

To establish such a criterion it is also necessary to find the factors which primarily determine the level of friction.

Thus the knowledge of the primary factors that determine the friction of polymers is necessary both to solve questions connected with their introduction as a bearing material and to improve the antifriction properties of such materials.

The object of the present work is to investigate the friction of polyamides on steel as it relates to the operating conditions of bearing materials, and to find the basic factors on which the value of their friction depends.

CHAPTER I

PRINCIPAL RELATIONS OF THE FRICTION OF POLYMERS IN THE

ABSENCE OF LUBRICATION

The Effects of the Load on the Friction of Polymers

The dependence of the frictional force on the load has been studied by various workers on polyamides, polyethylene, polymethyl methacrylate, polytetrafluoro-ethylene, yarns, rubbers, and other materials.

The tests were run on friction according to the schemes: "sphere-plane," "crossed cylinders," "crossed fibers." The materials of the mated surfaces were metals, plastics and glass.

The experiments were run mostly without lubrication at low sliding speeds (of the order of 0.0001 m/sec), thus excluding any appreciable heating of the friction surfaces. Of all the multitude of formulas obtained by investigators for the load dependence of the frictional force F, two main types may be distinguished.

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The first type includes the basic formula used to describe the friction of solid bodies,

$$F = \mu_0 P + \alpha S_\phi, \qquad (1)$$

whence

$$\mu = \mu_0 + \alpha \frac{S_\phi}{P},$$

where α, μ_0 are coefficients; S_ϕ is the area of actual contact; P is the load; and μ is the coefficient of friction.

This formula was first proposed by Coulomb. It was experimentally verified in a number of works in the study of the friction of fibers and rubber /2-8/. It was somewhat developed by S. B. Ratner, who investigated the static friction of rubbers /9/.

A number of authors investigating the friction of polymers in the form of fibers and specimens of other shape, have established relations of a second type /10-17/

$$F = aP^n \qquad (2)$$

whence

$$\mu \approx P^{n-1}$$

where a is a coefficient; $0.67 < n < 1$. They have also shown that the frictional force of the polymers is proportional to the area of actual contact, i.e.,

$$F = cS_\phi, \qquad (3)$$

where

$$S_\phi = kP^n; \qquad (4)$$

k is a coefficient; $0.67 < n < 1$;

The value of n is determined by the character of the deformation, intermediate between pure elastics and plastics /11/, by the character of the contact /16-18/, by the shape and dimensions of the contact surfaces and their roughness /15, 19, 20/, by the character of the curvature of the supporting surface, etc. /21/. The formula

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obtained by G. M. Bartenev based on the molecular-kinetic theory of friction developed by him /22/ is of different form:

$$F = c_1 S_\phi + c_2 S_u \omega P \tag{5}$$

where c_1, c_2 are coefficients depending on the sliding speed, the temperature and the molecular constants; S_n is the nominal area of contact; and   is a quantity characterizing the effect of the load on the adhesive force.

In view of the fact that the second term in Eq. (5) is usually small /23/, this formula can be reduced to Eq. (4), which corresponds to the proportionality of the frictional force to the area of actual contact.

According to References /24 - 25/, at small loads Eq. (5) passes over into the formula of Coulomb or Amonton.

In all the above studies, a decrease in the coefficient of friction of polymers, including polyamides, was observed with increasing load. This decrease in the coefficient of friction is particularly sharp at small loads in fiber friction.

Taking account of the views developed by B. V. Deryagin on the friction of solid bodies /26-27/, which consider the possibility of a variation of the frictional force independently of the area of actual contact, the theoretical correctness of the correlation of the frictional force only with the area of actual contact of the body may be doubted.

According to data of I. V. Kragel'skiy and V. S. Shohedrov /28/, on the friction of metals, the frictional force is determined by the values of the unit pressures on the areas of actual content, which depend both on the elasto-plastic properties of the material, and on the shape of the surface irregularities and the character of the curvature of the supporting surface.

It would seem that in the case of polymers the frictional force cannot depend only on the area of actual contact. However, the agreement in the character of the load dependence of the frictional force, Eq. (2), and the load dependence of the area of actual contact, Eq. (4), speaks for the view that while there do exist

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factors distorting these relations their influence is clearly small and practically speaking it is precisely this variation in the area of actual contact that is of decisive importance in the load dependence of the frictional force for polymers.

In connection with the fact that in the friction of polymers on steel and other materials the character of the load dependence of the frictional force is subject to the predominant influence of the variation of the area of actual contact and are close together for all polymers, it would be difficult to draw any conclusions at all about the features of the interaction between frictional materials based only on this single relation.

The Influence of the Sliding Speed on the Friction of Polymers

Only a few authors have studied the influence of the sliding speed on the friction of polymers. Let us briefly consider the results of the most important of such studies.

Gralen and Olofsson /3/, investigating the friction of fibers against fibers in a relatively narrow range of speed (at $V < 1.5$ cm/sec), obtained only a small decrease in the coefficient of friction with increasing sliding speed. This permitted the conclusion that the coefficient of friction μ of fibers, including polyamide fibers, is practically independent of the sliding speed. A certain increase in μ with decreasing speed, as well as the fact that the value of μ_s is greater than μ_k, is explained by Olofsson /6/ as the result of the more complete contact and the engagement between the surface irregularities (μ_s and μ_k are the respective static and kinetic coefficients of friction).

Milz and Sargent /29/ studied the friction of a number of polymers. Their tests were run on the scheme of intersecting cylinders, one of which was steel at sliding speeds of 4.0 to 186.5 cm/sec. The speed had a different effect on the variation of the coefficient of friction of different polymers. Thus in the polyamides he observed an increase in the coefficient of friction with increasing

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speed up to a certain value (61 cm/sec), which subsequently held constant. The same was observed in the friction of polytetrafluoroethylene with fillers of molybdenum disulfide or copper. A similar relation was obtained for polytetrafluoroethylene by other authors /30-31/. In some polymers, however (polystyrene and cellulose acetate) the coefficient of friction declined with increasing speed in the same range.

Milz and Sargent relate the character of the dependence of μ on the sliding speed to the difference in the relation between the static and the kinetic component when a discontinuous displacement, "gripping-slipping," takes place.

Sporkert and Hahn /32/ ran experiments on the friction of various polymers against steel in the scheme "sphere-plane." When the speed was increased to 1 cm/sec, they observed a decline of the coefficient of friction. On further increase of the speed to 10 cm/sec, the coefficient of friction of various polymers, including polyamide and polytetrafluoroethylene, increased.

Studies by many authors /13, 33-35/ have shown that on friction of rubbers against a hard base (glass or metal) the coefficient of friction increases with sliding speed. This increase continues until other factors, heating or vibration, begin to exert the decisive influence on the character of this relation.

Ye. A. Chudakov /36/ explains the increase in the force of friction of rubber with increasing sliding speed by the fact that, since rubber is an elastic body, the sliding of various surface elements at low speeds is not simultaneous. This causes what might be called an incomplete utilization of the normal force in the formation of the frictional resistance. With increasing speed, the number of elements sliding simultaneously increases, and the force of friction also increases. The explanation of the increase of frictional force with speed proposed by G. M. Bartenev and A. Shallamakh is closely related with their views on the mechanism of friction of rubber. This question will be discussed in more detail below.

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On the basis of the above we may note that in various polymeric materials the sliding-speed dependence of the coefficient of friction takes different forms:

a) the coefficient of friction of rubber increases with increasing sliding speed within certain limits;

b) for plastics, no single character of variation of the frictional force with sliding speed is observed. Since the studies have covered only rather narrow ranges of sliding speed, which have not been the same, and have been performed under various conditions, it is difficult to establish any general law of variation of friction for various groups of plastics or polyamides.

The existing difference in the speed dependence of the frictional force in various polymers is consistent with the view that the peculiar properties of polymers themselves affect the character of this relation.

The Influence of Temperature on Polymer Friction

The peculiar mechanical and structural features of polymers result in a sharp temperature dependence of their physico-mechanical properties. There is little information, however, on the temperature dependence of the frictional force of polymers. No studies at all have been performed on the temperature dependence of polyamide friction.

Shooter and Thomas /37/, investigating the friction of polymers against each other and in pairs with steel on the scheme "sphere-plane" in a number of polymers, observed a certain increase in frictional force with temperature. Polystyrene showed the greatest growth. A temperature rise from 20 to 80°C increased the coefficients of friction from 0.5 to 0.65-0.70.

A temperature rise to 200°C had no effect on the friction of polytetrafluoro-ethylene against polytetrafluoroethylene, nor against steel, but did increase the coefficient of friction of steel against polytetrafluoroethylene from 0.09 to 0.14.

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King and Tabor /38/ investigated the effect of temperature on the mechanical properties and coefficient of friction of polyethylene, polytetrafluoroethylene, polytrifluoroethylene and polymethyl methacrylate.

The test was run on the scheme "sphere-plane" on pairs of similar materials. The authors found that the coefficient of frictions for the polymers investigated varies in accordance with the ratio S/H, where $\underline{S}$ is the shear resistance of the polymer in bulk and $\underline{H}$ is the hardness, from the unrestored impression from indentation by a ball.

A study of M. M. Khrushchov and Ye. M. Shvetsova showed that temperature has a different effect on the coefficient of friction of brake-shoes of different materials: in some cases it increased that coefficient, and in other cases decreased it /39/.

In the opinion of I. V. Kragel'skiy anu Troyanovskaya /40, 41/. the difference in the character of variation of the coefficients of friction with temperature is due to the different character of the variation of the mechanical properties of plastics, their hardness, toughness and shear resistance.

In a study of rubbers /35/, /42/, it was found that the frictional force declines sharply with increasing temperature, but that an increase in temperature above a certain level leads to the rise of that force.

In studies performed at constant tensile force, Schallamach obtained the following temperature dependence for the sliding speed of rubber:

$$V_{F=\text{const}} = A_{F\text{кр}}(-E_1'/RT),$$ (1a)

where V_F = const is the sliding speed at constant tensile force; A_1, E_1 and $\underline{R}$ are constants, and $\underline{T}$ is the absolute temperature.

Based on the form of dependence obtained, he proposed that the friction of rubber is a process related to activation. It is precisely by this that the character of the temperature and speed dependence of the coefficient of friction

of rubber is determined. With this treatment, the role of that part of the frictional force connected with wear and deformation is excluded from consideration. He considers the share of the friction related to wear to be negligible. He does, however, show a substantial influence of deformation and of the changes in the physical properties of the surface layers of rubber during friction on the value of the frictional force /42/.

On the basis of these data it may be concluded that the character of the temperature dependence in polymeric materials varies. In the rubbers, when the temperature increases to a certain level, a sharp decline in the coefficient of friction is observed. In plastics, a temperature rise has various effects on the frictional force. The nonuniform temperature dependence of the frictional force among various polymers permits the conclusion that specific properties of the polymers affect the character of these dependences.

Some Peculiarities of the Properties of Polyamides

Polyamides are compounds containing peptide groups between hydrocarbon chains. Their structure corresponds to the general formula - NH - R - CONH-R-CONH, where R are hydrocarbon chains with several CH_2-groups.

The polyamides presented in Table 1 are today the most widely used in the USSR for technical purposes.

Figure 1 /43/ shows the structure of a polyamide with oriented chain molecules.

The NH groups are for the most part attached to the CO groups of the adjacent molecules by means of hydrogen bonds. The presence of intermolecular hydrogen bonds, increasing the energy of intermolecular cohesion, is of decisive influence on the properties of polyamides: the melting point, the modulus of elasticity, the rigidity, etc. But since not all the polar groups of the neighboring molecules are able to form hydrogen bonds, owing to the distance between them, some of them are present in the polyamide in the unbonded state /43, 44/.

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Table 1

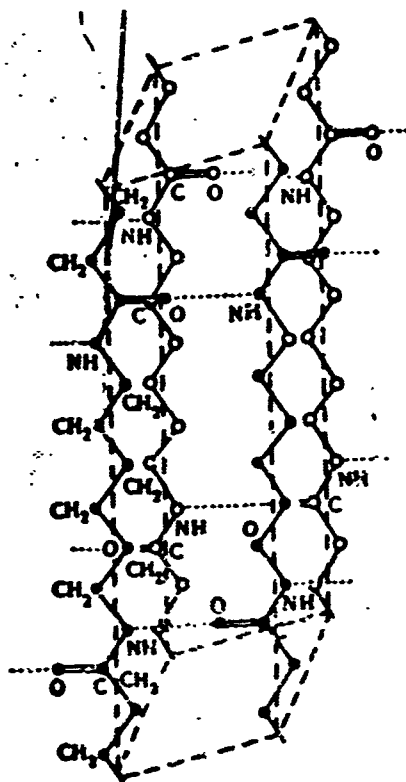| Name		Simplified Chemical Formula	Specifica-tions
Technical	Chemical		
Capron	Polyoaprolactam	$(-NH(CH_2)_5CO-)_n$	VTU UKhP No. 69-58
AK-7	Polyhexamethyleneadipamide (for the most part)	$(-NH(CH_2)_6NHCO(CH_2)_4CO-)_n$	VTU No. M90-57
P-68	Polyhexamethylenesebacamide	$(-NH(CH_2)_6NHCO(CH_2)_8CO-)_n$	TU GKhP No. M617-57

Fig. 1. Structure of polyamide with oriented chain molecules /43/.

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Polyamides are crystalline polymers /45-46/. The crystals, in the form of plates and needles, are formed by polar peptide groups, between which flexible polymethylene segments are located in random arrangement. The molecular chains pass through the crystals in transverse direction /47, 48/.

As shown by the studies of V. A. Kargin, G. L. Slonimskiy, and T. I. Sogolova, crystalline polymers possess peculiar properties which differ sharply from those of amorphous polymers. The ideas of three physical states, of the value of the dimensions and of the flexibility of the chain molecules of amorphous polymers /49-51/ cannot be directly applied to crystalline polymers /52-54/.

In contrast to amorphous polymers, the curves of deformation of crystalline polyamides ˩ ve regions of elongation sharply demarcated from each cther.
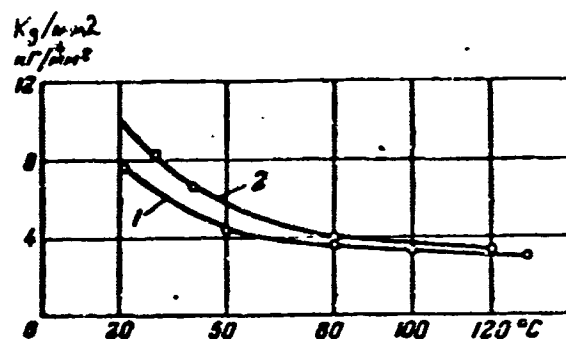
Fig. 2. Temperature dependence of hardness of polyamides according to data of /57/:
1 - capron; 2 - P-68

Another peculiarity is the considerable increase in the modulus of elasticity under the influence of great mechanical stress. In connection with the structural peculiarities of polymers and the existence of long chain molecules, completely crystalline polyamides do not exist. The degree of crystallinity depends on the rate of cooling from the melt and on the subsequent heat treatment.

The mechanical properties are primarily determined by stress and temperature. The molecular weight, orientation, moisture content and other factors exert a great influence /54-56/.

Table 2

Property	Polyamides			OTsS 6-6-3 Bronze (chill cast) Bronze /58/
	Capron	AK-7	P-68	
Short-time tensile strength σ_b, kg/cm^2	600-650	500-650	400-500	1800-2500
Modulus of elasticity in tension, E, kg/cm^2	-	15000	12100	900,000
Brinell hardness HB, kg/cm^2	10-12	15-18	14-15	65-75
Specific gravity γ, g/cm^3	1.13	1.14	1.11	8.82
Coefficient of linear expansion α per 1°C	$10-18 \cdot 10^{-5}$	$10-11 \cdot 10^{-5}$	$11-12 \cdot 10^{-5}$	$1.7 \cdot 10^{-5}$
Coefficient of thermal conductivity λ, cal/°C-cm-sec	$6-8 \cdot 10^{-4}$	-	-	$2240 \cdot 10^{-4}$
Melting point t, °C	215	240-243	210-215	960

Figure 2 shows the variation of hardness of several polyamides, according to data of A. D. Kuritsina and P. G. Meystner /57/.

Table 2 gives the principal physicomechanical properties of polyamides (according to data of the Plastics Research Institute) and also the data for OTsS bronze 6-6-3.

By comparison with bronze OTsS 6-6-3, the polyamides are distinguished by a low coefficient of thermal conductivity, a high coefficient of thermal expansion, a relatively low melting point, and a low specific gravity.

Effect of Heat Treatment on the Friction of Polyamides

The data on the influence of heat treatment of polyamides on friction are incomplete and scattered.

Jacoby /59/ investigated the influence of heat treatment on deformation and the coefficient of friction of polyamide bushings. The heat treatment consisted in

holding the articles in machine oil at $150^{\circ}C$ for 24 hr. Before testing the specimens were kept in water for 24 hr. After heat treatment the coefficient of friction in test without lubrication in a pair with steel according to the scheme "shaft-bush" at a load of 65 kg/cm^2 decreased from 0.23 to 0.19, but at load 150-200 kg/cm^2, there was no difference. The deformation of polyamide in a friction unit under load decreased from 5% to 0.5%.

No changes on examination of the structure in polarized light were detected.

Olsen /60/ investigated the effect of heat treatment of polyamides on certain mechanical properties and on their structure. He subjected specimens of polyamides (first dried in vacuo at t = $60^{\circ}C$ for 10 days) to a heat treatment consisting in prolonged holding at 100, 120 and $150^{\circ}C$ in various media: machine oil, in an atmosphere of CO_2, in a jet of steam, and in molten salts. All forms of heat treatment led to a certain increase of hardness (10-20%). The author notes, however, that the improvement in mechanical properties is lost after absorption of moisture by the specimen.

No changes could be detected on examination of sections of the polymer by polarized light.

According to the experimental results of Czech workers /61/, heat treatment in hot oil at 160 or $180^{\circ}C$ significantly increases the hardness of polyamides. Figure 3 shows the variation in the hardness of capron according to these data.

The melting of the surface layers of polyamide by infrared irradiation or by a blast of hot air followed by slow cooling leads to the appearance of spherulites in the structure and to an increase in surface hardness. The coefficients of friction decline, particularly with good lubrication. The wear resistance is considerably increased /62/.

In these studies, except for the examination of thin sections of polymer in polarized light, no structural studies were performed. At the same time, several

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investigators did specially study the structural changes in heat treatment, using the methods of X-ray analysis.
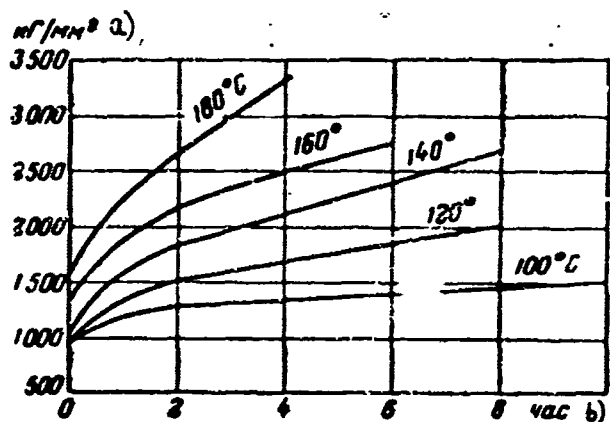
Fig. 3. Hardness of capron plotted against temperature and duration of heat treatment /61/.

a) kg/mm^2 b) hr

The results of Fuller, Baker and Pape /46/ distinctly showed an increase in crystallinity in slowly cooled specimens (t = 204°C) and indicated that the conditions of crystallization were better in polyamides slowly cooled in the range 200-215°C than in those held for a longer period at a lower temperature (200°C). An increase in crystallinity was also observed at 160°C. With increasing temperature, however, the degree of crystallinity also increased.

I. V. Mikhaylov and V. O. Klesman /63/ also found that when capron, rapidly cooled from the melt, was heated to 175-180°C, it passes from the nonequilibrium undercooled amorphous state to the equilibrium crystalline state.

A change in the form of the X-ray patterns was also found after heat treatment at lower temperatures /64/, which indicates that the process of crystallization of a polyamide commences at temperatures even lower than the glass transition point, but proceeds slowly. On approaching the glass transition point, the rate of crystallization increases and is more and more accelerated with increasing temperature.

These data are evidence that on heat treatment, under certain conditions, the polyamides undergo structural changes. Degradative processes also take place during heat treatment /65/. Under the action of temperatures over 90°C and other factors (ultraviolet irradiation or acids) the following processes may take place in polyamides:

(1) cleavage of the molecules at the C - N bonds of the peptide group, forming smaller molecules of the same chemical structure;

(2) a change in the degree of crystallinity or local order in the molecular arrangement, including a change in the packing of the hydrocarbon segments, a redistribution of the dipoles and hydrogen bonds;

(3) a change in the quantity of firmly bound water, and also of the organic liquids serving as plasticizers.

The holding of polyamides at elevated temperatures, especially in presence of oxygen, causes a considerable decline in tensile strength /66/. Thus a stay of 10-12 hr at 100°C lowers the tensile strength by 12-14%. A temperature rise to 200°C for the same time lowers the tensile strength by 35-37%.

Thus many investigators have found changes in structure and the degradative processes in polyamides when held at elevated temperatures, although the effect of heat treatment on the antifrictional properties of polyamides has not been sufficiently studied.

Questions in the Theory of Polymer Friction

There are various views on the mechanism of polymer friction and the basic factors that determine it.

Some authors give data pointing to the existence of a correlation between polymer friction and adhesion.

Shooter and Thomas /37/ investigated the friction of polyethylene, polytetrafluoroethylene, polystyrene, and polymethyl methacrylate in pairs of the

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same substance. The coefficients of friction were found to depend on the molecular cohesion of the polymer. In this connection the authors assumed that the friction of polymer against polymer depends on the adhesion between the surfaces, which in turn depends on the molecular cohesion.

Bowers, Clinton and Zisman /67/, studying the friction of polytetrafluoroethylene and its derivatives, confirmed the influence of molecular activity of polymers on their friction.

They showed /10, 12/ that the expression for the coefficient of friction of polymers, including polyamides, according to the adhesion theory, is of the form

$$\mu = \frac{s}{\delta^{\frac{1}{r}}} = \frac{S}{H},$$

where s is the shear resistance of the bonds formed on friction; S is the bulk shear resistance of the polyamid; δ^1 is the resistance of the material to flow, equal to its hardness from the nonrestored impression (H), determined from the indentation of a ball.

On the basis of the closeness of the values of the shear resistance of the bonds formed on friction (s), and of the bulk resistance of the polymer to shear (S), Bowden, Tabor and others /68-72/ by analogy to the theory developed by them for metals, came to the conclusion that the mechanical friction of polymers and metals is fundamentally one and the same. Since the shearing of bonds takes place in the depths of the softer material, the polymer, the coefficient of friction is determined by the mechanical properties of the polymer: the shear resistance (S) and the hardness according to the unrestored impression (H).

Polytetrafluoroethylene is an exception. The shear resistance of bonds formed in it during friction is considerably less than its shear resistance in bulk.

In Bowden's opinion, the mechanism of friction in polymers and hard bodies differs only in details and is due to the differences in the chemical nature of the polymers and to the fact that polymers are highly elastic materials whose deformation depends on the geometry of the surfaces, the load and the loading time.

Studies by Greenwood, Tabor et al. /73, 74/ have shown that one of the sources of the formation of a frictional force by rubber and other polymers may be the deformation losses. In cases where the adhesion between the surfaces is small and the local deformation is relatively great, which may be the case in lubricated friction, the friction can be determined almost entirely by hysteresis losses.

G. M. Bartenev /75, 76/, and Schallamach /35/ treat the mechanism of rubber friction as a molecular-kinetic process. On contact of rubber with the surface of a solid body, its molecular chains adhere to that surface. The number of chains in contact with the surface of the solid body depends on the roughness and the value of the normal pressure. Each chain is in contact for a limited time, and then makes a jump to a new site of contact. On application of an external force, the conditions are established for a jump primarily in the direction of the force.

For the friction of rubber of any degree of roughness against a smooth hard surface (with microprojections <50 Å high), G. M. Bartenev arrived at the following expression for the sliding speed at low values of the force $\underline{F}$:

$$V = \frac{\lambda \gamma F}{2\tau_0 KT} e^{\frac{U}{KT}} \tag{8}$$

and at high values of the force $\underline{F}$

$$V = \frac{\lambda}{\tau_0} \sqrt{\frac{KT}{2\pi\gamma F}} e^{\frac{U-\gamma F}{KT}}. \tag{9}$$

where λ is the mean distance between adjacent sites of contact; $\gamma = \lambda/2N_k$; N_K being the number of chains in contact with the surface of the solid body; $\underline{K}$ is the Boltzmann constant; $\underline{T}$ is the absolute temperature; and $\underline{U}$ is the energy barrier.

On the basis of the formulas, at $F = 0$, the sliding speed of rubber is 0.

The author draws the conclusion that the dry friction of rubber is an arbitrary quantity depending on the accuracy of measurement and the experimental conditions, and, in contrast to the dry friction of hard bodies /77/, is characterized by the fact that the force and coefficient of friction at rest are both 0. Somewhat later, on the basis of an analysis of the results of Durwell and Rabinowicz /78/, who

found a sharp decrease in the coefficient of friction of indium with decreasing sliding speed to 2×10^{-9} cm/sec, G. M. Bartenev and G. I. Epiphanov came to the conclusion that the molecular component of friction of a rubber-like polymer resembles that of a metal, both being of molecular-kinetic nature /79/.

G. M. Bartenev considers that his theory of friction can be applied to the friction of other high-polymer amorphous materials at temperatures above the glass transition point.

S. B. Ratner, from a comparison of certain features of the process of friction of rubber with the friction of hard bodies comes to the conclusion that the laws of friction of rubber and hard bodies are in many respects analogous, which indicates the presence of similar elements in their mechanism /80/.

Ratner bases his work on the applicability of the molecular theory to the friction of rubber /81-82/.

I. V. Kragel'skiy, starting out from the general propositions developed by him in the molecular-mechanical theory, considers the frictional force of rubber (F) as the sum of two components /83/:

$$F = F_{mol} + F_{def}$$

where F_{mol} is the component of the frictional force due to molecular interaction and F_{def} is the component of that force due to deformation. In turn,

$$F_{mol} = \tau_{mol} A_r$$

where τ_{mol} is the specific molecular force of friction;

A_r is the area of actual contact, and

$$F_{def} = W/d,$$

where $\underline{W}$ is the work of repulsion of the material;

d is the diameter of the contact spot of a contacting projection.

Thus various views on the mechanism of friction of polymers exist today. A number of investigators, besides G. M. Bartenev, defend the correctness for polymers of one theory or another of the friction of hard bodies. I.V. Kragel'skiy starts

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out from the applicability of the molecular-mechanical theory to polymers. Many foreign workers base their studies on the adhesion theory. S. B. Ratner considers that the molecular theory is true for polymeric materials.

To elucidate the applicability of any of the above theories of friction to the friction of polyamides, an experimental study is required.

It is also clear from the above survey that on the basis of the data now available no complete representation can be formed about the behavior of polyamide under friction, and the principal factors on which the value of the frictional force depend can likewise not be established.

The speed dependence of the friction of a polyamide over a wide range of speeds has not been investigated. Yet a knowledge of this dependence might give valuable information on the mechanism of interaction in friction. The range of speeds in the existing studies does not exceed a factor of 50.

The effect of temperature on the friction of polyamides has not been studied at all.

The effect of heat treatment has been insufficiently investigated.

In connection with the above, we performed an experimental study to elucidate the following questions:

(1) the influence of load, sliding speed and temperature on the friction of polyamide;

(2) the effect of heat treatment on the hardness and friction of polyamide;

(3) to find the principal factors determining the friction of polyamide against steel under the operating conditions for bearing materials.

CHAPTER II

TEST APPARATUS AND METHOD

The friction of polyamide against steel was investigated for the friction of
the specimens according to the following schemes: "shaft-partial bushing,"
"sphere-plane" and "shaft-bushing" on specially designed apparatus and devices.

The test on the scheme of "shaft-bushing" was run on a stand of the Department
of Metallurgy and Materials, ENIMS /Experimental Research Institute for Machine
Tools/.

Apparatus for friction and wear testing on scheme "shaft-partial bushing."
The test apparatus for friction and wear was based on the Skoda-Savin machine
(Fig. 4), in which the disc 1 abrades the specimens 2, held in the clamps 3. Under
the action of a load, the body of the working head is lowered as the specimen is
worn down. The wear is estimated by the aid of the indicator 4.

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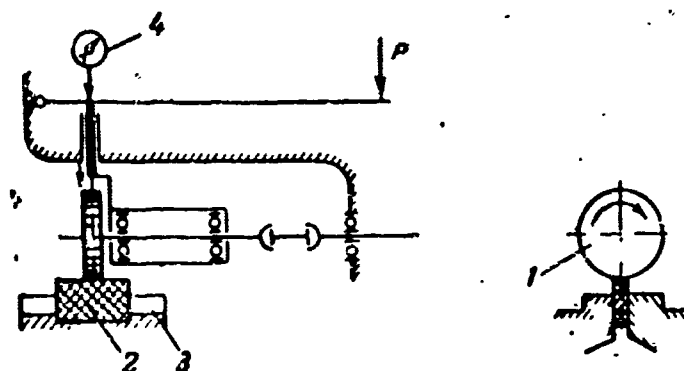
Fig. 4. Schematic diagram of operating unit of Skoda-Savin machine.

The newly designed apparatus, differing from this machine, runs the test on the scheme of "shaft-partial bushing" (Fig. 5). In designing the loading system, the base was the scheme of the parallelogram previously used in the "R" machine /84/. The shaft of the machine is the steel disc 1, and the specimens are the bushings 2, made of the test polymer.

The body of the attachment 3 is fastened to the stand. The load R is transmitted to the lever 5 through the lever, the plunger 4, and the annular bracket. One end of it is hingedly attached to the body 3, the other end hingedly attached to the crosspiece 6, connected by the straps 7 to the clip 8, in which the specimens 2 are fastened. All the supports are knife-edge.

Fig. 5. Schematic diagram of apparatus for friction and wear tests according to scheme of "shaft-partial bushing."

Under the action of friction, the clip 8 tends to rotate together with the disc. It is prevented from rotating by the string connected to the flat spring 9. The clip is fixed in axial direction by the aid of the fluoroplast F-4 support, placed in the groove of the clip. Arrangements are provided for adjusting the position of the clip in axial direction and on the circumference of the disc.
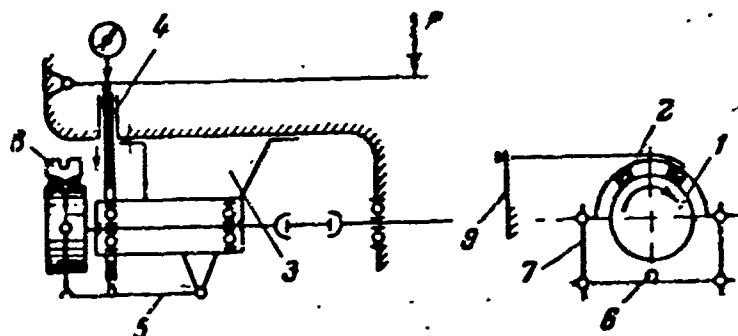
The wear is evaluated by the aid of the indicator of the Skoda machine from the depression of the clip attached to the plunger 4. The indicator is graduated in one-micron scale divisions.

The force of friction is measured from the deformation of the flat ring by the aid of resistance sensing elements.

This apparatus permits testing under loads of 0.05 to 25 kg, at sliding speeds of 0.167 to 2.5 m/sec, with and without lubrication. In the latter case a special funnel directing the lubricant to the friction surface of the disc is attached to the clip. The diameter of the discs is 30 mm, and the width is 6 mm. The material and finish of the friction surface may be varied according to the object of the study.

The specimens used in the test are prepared in the form of the strips 1 (Fig. 6, a) 2 x 2 x 5 mm, attached to the steel body of the partial bush 2 by means of the wedges 3, or in the form of partial bushes themselves (Fig. 6, b). The
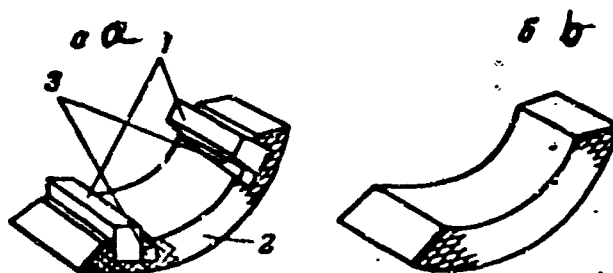

Fig. 6. Examples of partial bushings.
a - assembled;   b - integral

partial bushes are installed in the groove of the clip 8 (Fig. 5) in the form of a "dovetail" and are fixed in lateral direction by two supports. The friction

surface of the specimens is finally finish-ground after they have been placed in the machine. Instead of the working disc a disc of the same dimensions with emery paper pasted on its outer surface is placed in the machine. The grinding is continued until the surface of the specimens is completely fresh and the height required has been attained.

Device for testing with artificially heated specimens is employed in conjunction with the above-described apparatus.
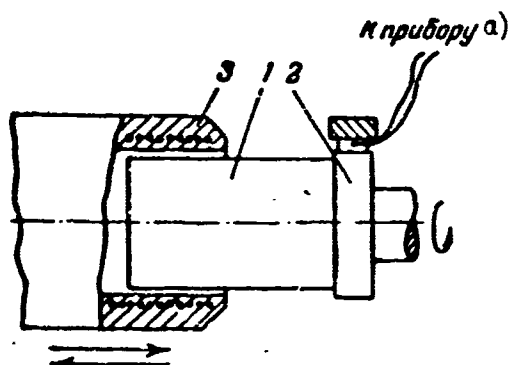
Fig. 7. Schematic diagram of apparatus for friction testing with artificial heating of specimens.
a) to instrument

The copper rod 1 is tightly pressed against the working disc 2 and rotates together with it. The heating is by the aid of the tubular electric heater 3, fastened in the clamps of the machine and moving on the rod with the clearance of 1 mm. The heat is regulated by an autotransformer. The temperature is measured in the specimens at a distance of 1 mm from the surface of friction by the aid of copper-constantan thermocouples 0.04-0.06 mm in diameter. The cold junction is placed in a thermally insulated space whose temperature is checked by a thermometer.

Device for testing under various heat-removal conditions. The heat removal conditions through the shaft were varied by means of artificial cooling of the disc (Fig. 8). On a copper rod, tightly pressed against the disc, the corrugated ring 1 is screwed. Part of this disc is submerged in the water flowing through the small bath 2. The rate of water flow is adjusted according to the desired degree of

cooling of the specimens. If necessary, the water coming from the main is further cooled in the coil 3, submerged in a vessel with melting ice.

The rate of water flow and its initial temperature are regulated in order to vary the degree of heat removal within wide limits.
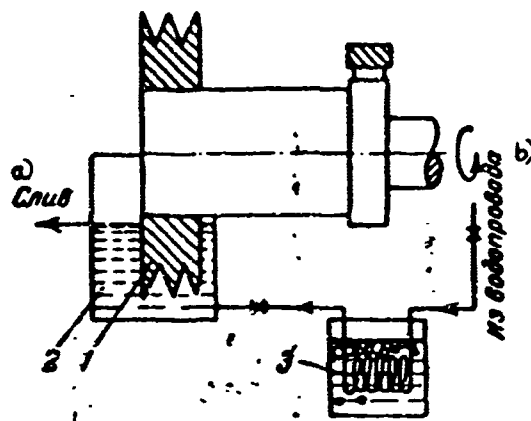
Fig. 8. Schematic diagram of device for friction testing under various heat-removal conditions.
a) discharge;   b) from water pipe

Device for testing of friction during translational motion of specimens. The friction during translational motion of the specimens was investigated on friction in the scheme "sphere-plane" on the apparatus shown schematically in Fig. 9.

On the guide frame 1 the carriages 2 and 3 are displaced. The flat specimen 4 is fastened on the stage of the carriage 2. The translational displacement is obtained by a lead screw driven by an electric motor through the reducer 5. The carriage 3 with the bracket 6 attached to it is displaced by rotating the handle of the lead screw. From the bracket, on suspensions on knife-edge supports, is suspended the plate 7, to which the rod 8 is attached by means of a stand and the two flat springs 9. To the lower end of the rod is attached a holder with the second specimen 10. Provision is made for heating it. It is lowered by placing the weights 11 on the arm of the rod 9.

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Fig. 9. Schematic diagram of device for friction testing on scheme of "sphere-plane" with progressive displacement of specimens.

The carriage 4 with the flat specimen, in moving, carries along the specimen 10. Its displacement is opposed by the spring 12 connected with the plate 7 by means of the spring 13.

The force of friction is estimated from the deformation of the spring by the aid of sensitive resistance elements. The rate of displacement of the flat specimens may be varied within wide limits, but in this work it was always 0.000003 m/sec. The load can be varied from 0.01 to 5.0 kg.

Heated indentor and stage for the Super-Rockwell instrument. Figure 10 gives the schemes of the indentor and stage. The spirals of the electric heaters 1 and 2 are used for the heating. The temperature of the specimens 3 is measured by copper-constantan thermocouples 4 (d ~ 0.1 mm) cemented into them. The temperature of the indentor ball is measured by the thermocouple 5, whose hot junction is calked into the indentor at a distance of 0.2-0.3 mm from the surface of the ball.

Stand for testing bushings in friction. Figure 11 shows the working unit of the stand. On the shaft of the machine are seated the removable steel bushings 1, whose outer surfaces are the friction surfaces. The upper clip 2 of the lowering

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apparatus rests on the ball bearings 3. To it is hingedly attached th's lower clip 4 with the test bushing 5 attached to it.
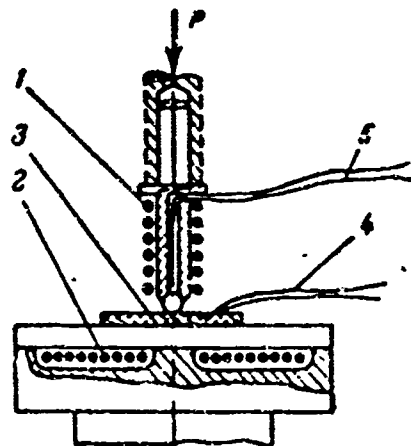

Fig. 10. Scheme of heated indentor and stage for Super-Rockwell instrument.
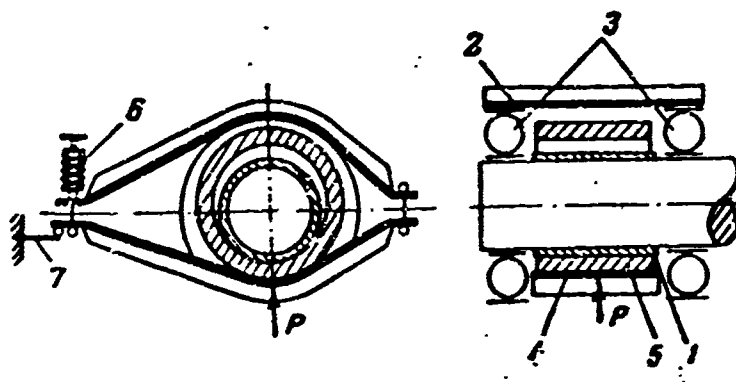
Fig. 11. Schematic diagram of working unit of test stand for bushings.

Lowering is accomplished by pulling the clips by the spring dynamometer 6, and in this case the bushing 5 is pressed against the shaft (bushing 1).

The frictional force is measured from the deformation of the flat spring 7, which keeps the apparatus from rotating during operation.

The friction in the ball bearir~ 3 is estimated from a special calibration.

Depending on the test regime ad ~ted, the lubricant is supplied either by a pump or by a special dropper.

CHAPTER III

STUDY OF FRICTION OF POLYAMIDES

Separation of specimens. The tests for the friction of polyamides against steel were run on the scheme of "shaft-partial bushing" on the machine shown by Fig. 5.

The discs were made of steel St.U10ЖПЗ-60-62. Their working surface was ground and polished before each test. The surface finish corresponded to $\triangle 7$.

After polishing, the discs were cleaned by a stiff brush under running water, dried with a cloth and washed twice with ether. The clip and other parts of the machine close to the friction surfaces were periodically rinsed with gasoline and ether.

The polymer specimens were in the form of bars, 2 x 2 x 5 mm. The friction surfaces of the specimens ($F = 20$ mm^2) were cleaned before the tests by a disc with emery paper under a load of 0.2-0.3 kg at 140 rpm.

The tests were run on polyamides (capron, AK - 7 and P - 68) in the air-dried state. The specimens were prepared from discs 2.5 mm thick, and 100 mm in diameter, cast in a cold pressure mold on a casting machine. The properties of the polyamide investigated corresponded to the standard specifications.

The effect of load on the coefficient of friction of polyamides. In the tests for friction without lubrication, the sliding speed was constant ($v = 0.22$ m/sec). The load was varied in the range from 0.5 to 4.5 kg (unit load 2.5-22.5 kg/cm^2). The loads over 2 kg were applied in two stages: the first stage was 2 kg and the full load was applied in 10-15 min. The wearing-in was under full load, lasting 1.5-3 hr and was completed by the total renewal of the specimen surface. In the test we took account only of the wear during the period at constant rate of wear and constant coefficient of friction. This period lasted from 1.5 to 7 hr. More prolonged tests were run at smaller loads.

Figure 12, a and b, shows the load-dependence of the coefficient of friction and the rate of wear of capron, in microns per km of sliding travel.

In the second series of tests, after finishing the final grinding, the load was suspended in stages, beginning with a minimum (0.5 kg) up to the load corresponding to a sharp increase in the coefficient of friction. The duration of the tests for each stage assured a constant frictional force for not less than 30 min.

The load dependence of the coefficients of friction of the test polyamides, in the form of the mean values of the results of three tests of each polymer, are shown in Fig. 13.

It will be seen from Figs. 12, a and 13, that at loads up to 1 kg a certain increase in the coefficient of friction with increasing load is observed. A sharp increase in the coefficient of friction when a certain "critical" load is exceeded is accompanied by apparent adhesions of the polyamide to the disc and a decrease in the rate of wear.

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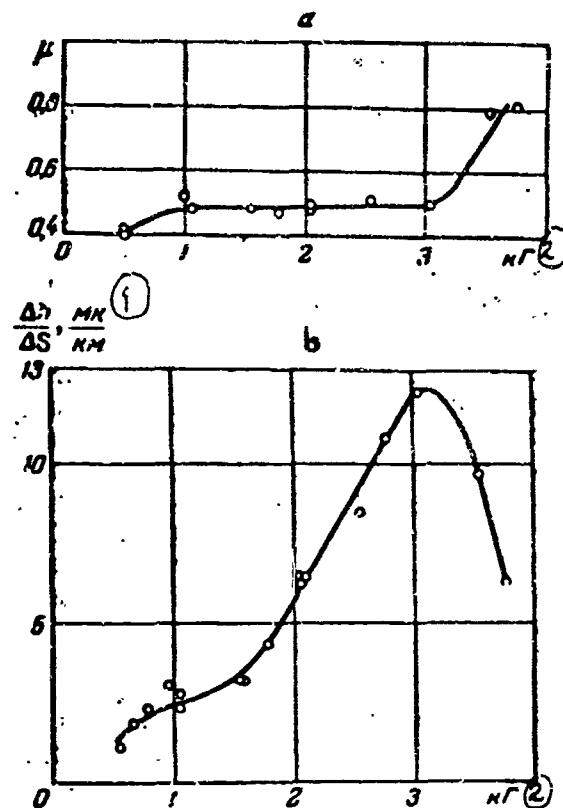Fig. 12. Load dependence of coefficient of friction (a) and rate
of wear (b) of capron.

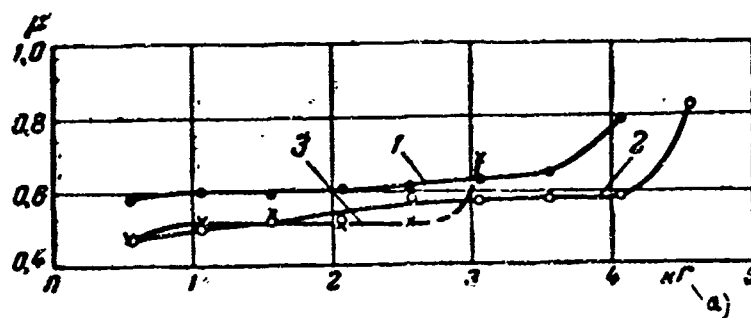1. $\Delta h/\Delta S$, μ/km   2. kg

Fig. 13. Load dependence of coefficient of friction of polyamides.
1 - P-68; 2 - AK-7; 3 - capron.   a) kg

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The changes on the friction surface at loads above critical are of a certain interest. The friction surface of the disc with adhering particles of polyamide is shown in Fig. 14, a and b. With increasing thickness of the adhering layer, it is scraped off by the specimen. On Fig. 14, b, two flakes of polyamide can be seen before their separation from the surface of the disc.

Further increase in the severity of the conditions causes melting of the surface layer of polyamide. The surface of the specimen is deformed and has a corrugated appearance (Fig. 14, c).

On the surface of the disc (Fig. 14, d), adhere extremely minute particles of molten polyamide, which roll down, combining into rather large formations disposed normally to the direction of sliding.
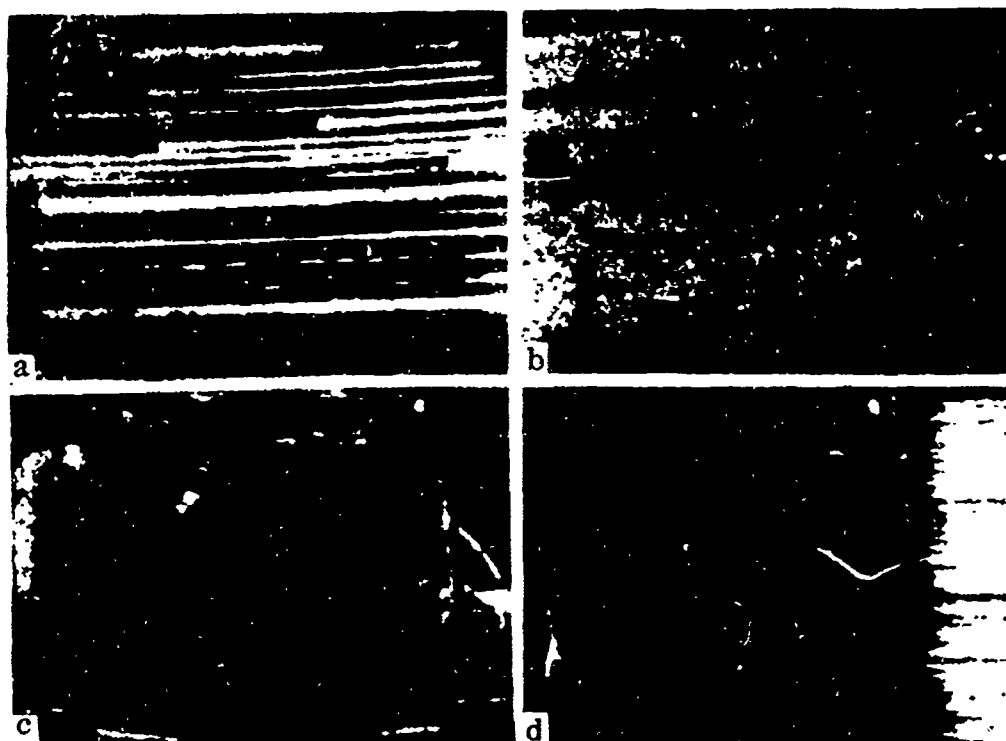

Fig. 14. Friction surface of discs and specimens of polyamides under various conditions.

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Thus the results of the tests show that the coefficient of friction of polyamides does not remain constant under varying load. At loads above the critical, the coefficient of friction rises sharply. This is the result of the changes taking place on the friction surface and manifesting themselves externally in the adhesion of particles of polyamides to the disc. The ra'' of wear when this happens decreases.

The results of these experiments differ from the results of other workers (Chapter I), in which the coefficient of friction of all polymers, including polyamides, declines with increasing load, for various schemes of friction.

Since in the above described tests, the specimen temperature increased with increasing load, while the studies discussed in the survey were run under conditions excluding any heating of the specimens, we may assume that the differences are connected with the influence of the temperature.

The influence of the sliding speed on the coefficient of friction of polyamides. The experiments were run in unlubricated friction on the above described apparatus (Fig. 5) using an additional reducer with a gear ratio of 1:16500.

The load was held constant at 1 kg (unit load equals 5 kg/cm^2). The sliding speed was increased in stages from 1.3 x 10^{-5} to 1.3 m/sec (from 80 x 10^{-5} to 80 m/min). The tests were long enough to assure constant coefficients of friction during each stage for not less than 15-30 min.

Figure 15 shows the dependence of the coefficients of friction of capron on the sliding speed. In connection with the great range of the speeds, a logarithmic scale is used for th, speeds.

The increase in the coefficients of friction with decreasing sliding speed in the range of very small speeds (the left branch of the curve) is apparently connected with the increased contact surface as a result of increased duration of the contact between the surfaces.
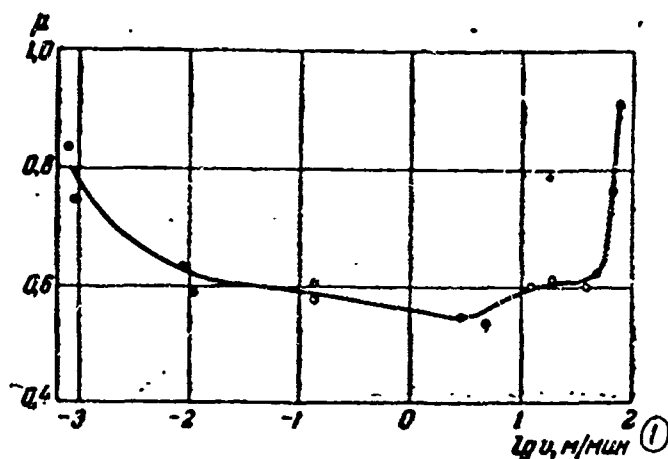
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Fig. 15. Coefficient of friction of capron vs. sliding speed.

(1) log v, m/min

In the range of speeds of the greatest practical interest (the right branch of the curve), the coefficient of friction increases with the sliding speed. Its sharp rise coincides with the appearance of polyamide adhesions on the steel disc.

A similar picture was observed in the earlier tests under loads above the "critical." This suggests that the cause of the sharp increase in the c‹ ‹ficients of friction is the same in both cases, and is connected with the rise in the temperature of the friction surface.

The results of the studies of the speed dependence of the coefficient of friction of polyamides considered in Chapter I are on the whole in agreement with those presented in this chapter and correspond to various regions of the curve (Fig. 15) covering a considerably greater range of variation of the sliding speed.

It does not correspond to the speed dependence of the coefficient of frictions found by other investigators for rubber.

The influence of temperature on the coefficient of friction. Temperature rise. The experiments were run on the apparatus (Fig. 5) with the attachment of Fig. 7, at a load of 1 kg (unit load 5 kg/cm^2) and a sliding speed of 0.22 m/sec.

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In unlubricated friction, under these conditions, the temperature of the specimens, measured at a distance of 1 mm from the friction surface, was 4-5°C above the temperature of the ambient air; in lubricated friction the difference was no more than 1°C.

Unlubricated friction. A series of tests was run on capron specimens. The electric heater was turned on after the final grinding was finished. The temperature was increased from 20 to 60-70°C in 3-4 hr. The rate of temperature rise in these experiments was varied. There were periods of constant temperature and of a certain decline.
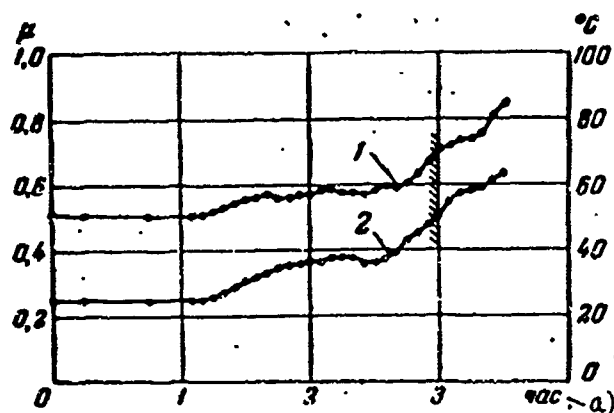
Fig. 16. Dependence of coefficient of friction (1) and temperature (2) of capron on artificial heating.

(a) hr

It will be seen from Fig. 16 that the curve of the coefficient of friction of capron follows the temperature curve rather distinctly. With increasing temperature an increase in the coefficient of friction is observed. The appearance of adhesions visible to the naked eye on the disc corresponds to a temperature of about 50°C (marked by the hatching on the figure).

A similar picture (Fig. 17) was observed in tests of other polymers: AK-7 and P-68.
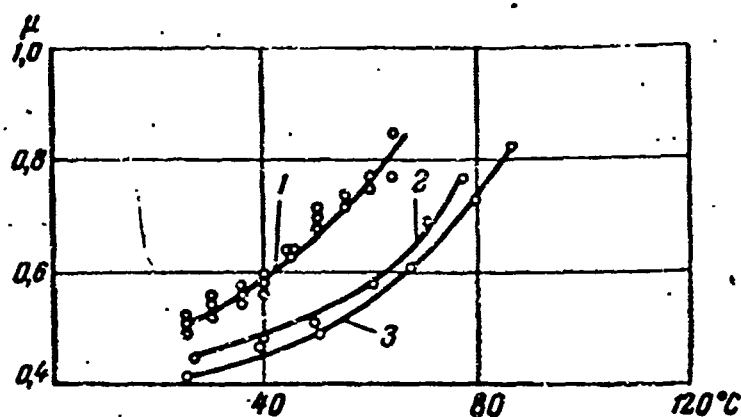
Fig. 17. Temperature dependence of coefficient of friction of polyamides under artificial heating.

1 - capron;   2 - P-68;   3 - AK-7

Lubricated friction. The tests were run on capron specimens. The lubricants used were industrial oils "12" and "45" which differ considerably from each other in viscosity (their specific viscosity at 50°C was 1.98 and 6.02 respectively). The lubricant was fed to the friction surface at the rate of 3 drops in 5 min. The rate of heating was in all cases approximately the same. The temperature of the specimens was increased until their surface layer melted.

In the well-polished specimens the friction before the heat was turned on was minimum, but its increase began immediately after the temperature rise commenced.

In the poorly-polished specimens with a higher initial friction, the increase in the coefficients of friction was somewhat delayed. At the end of the tests, however, the coefficient of friction was the same, regardless of the initial finish of the specimens.

The results show that on friction of capron lubricated by industrial oils the coefficients of friction with increasing temperature increases continuously (Fig. 18, a and b). It increases particularly when a less viscous oil is used. The melting of the surface layer of the specimen leads to a decrease in the coefficient of friction.

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The temperature of the capron specimen, measured at a distance of 1 mm from the friction surface at the instant that surface reaches the melting point of capron was on the average 160°C, corresponding to a temperature drop of 55°C.

To determine the sensitivity of the variation of the coefficients of friction to the variation of temperature in lubricated friction, the electric heater was periodically turned off and the temperature of the specimens declined, partially or completely.

From the results of one such test, using industrial oil "12," a graph was plotted (Fig. 19, a, b, c). It will be seen from it that the variation of the coefficient of friction distinctly follows the temperature.

From the results of the second and third heating (Fig. 19, b, c) the dependence of the coefficient of friction on the temperature measured at a distance of 1 mm from the surface was plotted (Fig. 20).

The relation obtained on the first heating is not included in the graph, since during the first test the specimens were additionally polished, thus facilitating the heating. The scatter of the experimental points is slight, indicating that the value of description is determined primarily by the temperature level, and that no irreversible changes occur on the friction surfaces with changing temperature.

Thus with increasing temperature in friction with lubrication by industrial oils, as with unlubricated friction, the friction of the polyamides increases continuously.

Decline of temperature. The tests were run in lubricated friction of capron specimens under a load of 1 kg (unit load 5 kg/cm^2) and a sliding speed of 0.22 m/sec.

To increase heat removal the device shown in Fig. 8 was used.

After completing the final polishing of the specimens a water bath* was applied to the ribbed disc, and the disc was partially submerged in the bath. The
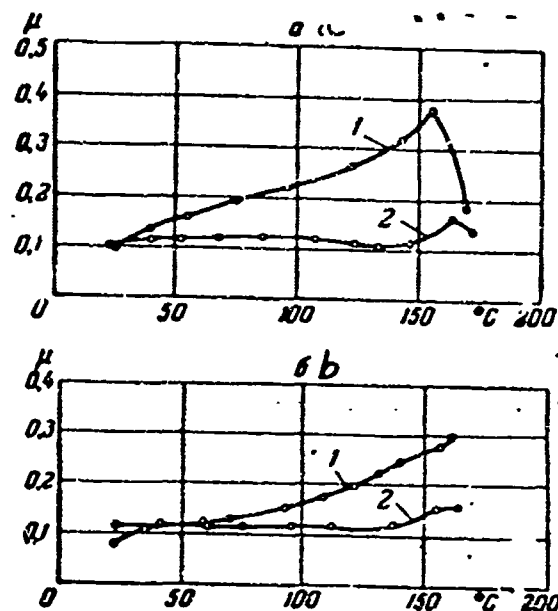
Fig. 18. Temperature dependence of coefficient of friction of capron with various lubricants.

a - industrial oil "12" (1), industrial oil "12" with 1% of oleic acid added (2); b - industrial oil "45" (1), industrial oil "45" with 1% of oleic acid added.
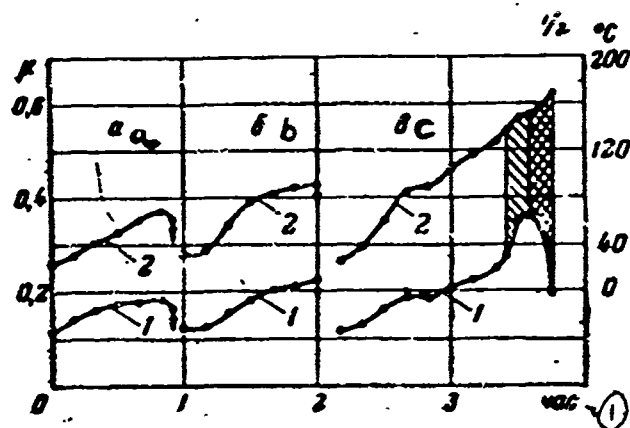

Fig. 19. Relation of coefficient of friction (1) and temperature (2) of capron specimens to period of artificial heating.

a - first heating; b - second heating; c - third heating. (1) hr
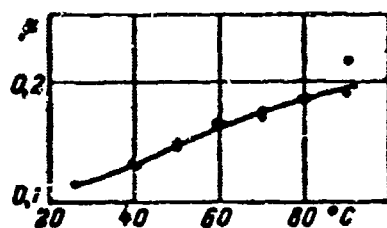
Fig. 20. Coefficient of friction of capron vs. temperature of specimens.

temperature of the specimens measured at a distance of 1 mm from the friction surface was 24-26°C before cooling, and by the end of the test it was 17°C, i.e., it declined by 7-9°C.

The coefficient of friction declined from 0.47 to 0.25 (by approximately half).

The character of the variation of the coefficient of friction on periodic cooling will be seen from Fig. 21. Interruption of the cooling leads to the restoration of the initial value of the coefficient of friction.

To check whether the vapor in the air condensed on the friction surface does not encourage the lowering of the coefficient of friction, we ran a special experiment. Under the cooled specimens, during the period when the coefficient of friction had not yet fallen to its final value, at a distance of 200-250 mm from the disc, a vessel with water heated to 40-45°C was applied for 1 sec. It was expected that if the fall in the coefficient of friction were due to the formation of a film of moisture, then its artificial formation on account of the condensation of the evaporated water would accelerate the decline in the coefficient of friction, but the effect was in fact the opposite. The coefficient of friction increased instantaneously by a factor of 1.5 and then slowly declined but did not reach its initial level during the experiment that lasted 1.5 hr.

Thus in the test with artificial cooling, as in the preceding tests with artificial heating, we found a sharp temperature dependence of the coefficient of friction of the polyamide.
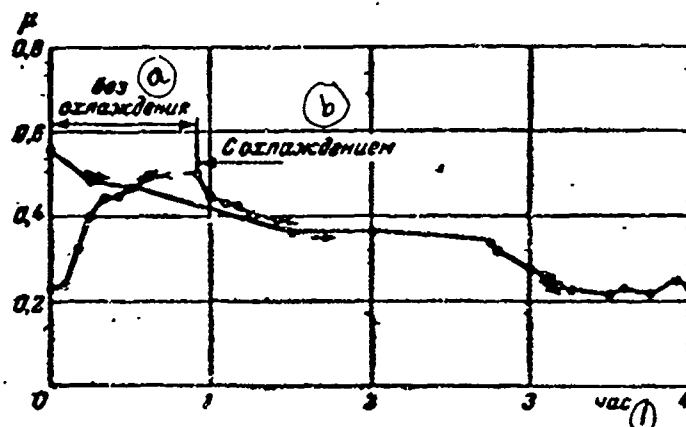
Fig. 21. Relation of coefficient of frict'on of capron to period of cooling.
a) without cooling; b) with cooling; (1) hr.

The existence of a sharp temperature dependence of the coefficion. of friction
of a polyamide indicates the justification of the previous hypothesis that the
temperature dependence exerts its influence on the character of the load dependence
and the sliding speed dependence of the coefficient of friction.

The reproducibility of the results, and the rather close agreement in the
variation of the coefficient of friction and the temperature, speak for the view
that the changes taking place on the friction surface are of reversible nature and,
other conditions being equal, are determined only by the temperature, which, in
turn, is determined by the heat removal from the unit.

For a combined evaluation of the effect of heat removal on the behavior of
capron during unlubricated friction, we ran a series of experiments. The tests were
performed on capron specimens according to the scheme "shaft-partial bushing"
(Fig. 4) with the device for artificial heating (Fig. 8) at loads of 1 to 9 kg
(unit load from 5 to 45 kg/cm^2) under sliding speed of 0.22 m/sec.

We determined the values of the coefficient of friction, the temperature and
the rate of wear $\Delta h/\Delta S$. The latter was determined from the decrease in the
thickness of the capron specimen during a disc travel of 1 km.

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On Fig. 22 the dashed lines show the mean results of the tests of three specimens obtained under normal heat removal and the heavy lines show the results with intensified heat removal.

It will be clear from the figure that under the same loads and sliding speeds the coefficient of friction, the rate of wear and the temperature of the specimens are all lower with intensified heat removal.
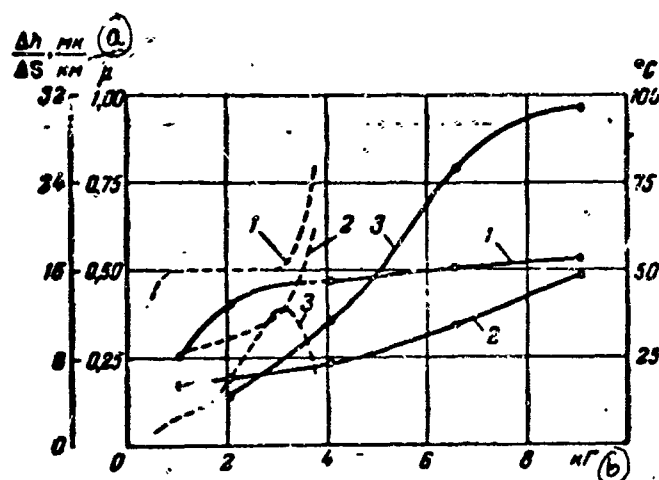
Fig. 22. Load dependence of coefficient of friction (1), temperature (2) and rate of wear (3) of capron specimens.

(a) $\Delta h/\Delta s$, μ/km   (b) kg

The shape of the curve is somewhat modified. There is an increase in the greatest load at which no adhesion and no sharp rise in the coefficient of friction are observed. In this case the critical load increased over three times.

Thus the tests to evaluate the influence of the temperature of the antifriction properties of polyamides show that the coefficient of friction, the rate of wear and the critical load of a polyamide all depend sharply on the temperature.

With rising temperature the antifriction properties of polyamides continuously decline.

Variation of the temperature of the surface layer of a capron specimen under conditions corresponding to the beginning of polyamide adhesion to the disc. The

experiments were run on the Skoda-Savin machine in cutting of the disc 1 into the specimen 2 at constant friction surface (Fig. 23, a).

The specimens were prepared by bonding two capron plates with a cement consisting of a solution of capron in a 10-15% aqueous solution of phenol. Between the plates was plr vd a thermocouple made of copper and constantan wires 0.03 mm in diameter. The hot junction was placed at a distance from the edge of the specimen such that, after cementing and finishing the friction surface, it would be approximately 0.4 mm from it. On finishing the friction surface, the specimen was fastened in the clamps. Instead of the working disc a disc of the same diameter, but made in the form of a milling cutter, was installed. The finishing was performed under translational displacement of the specimen relative to the rotating milling cutter.
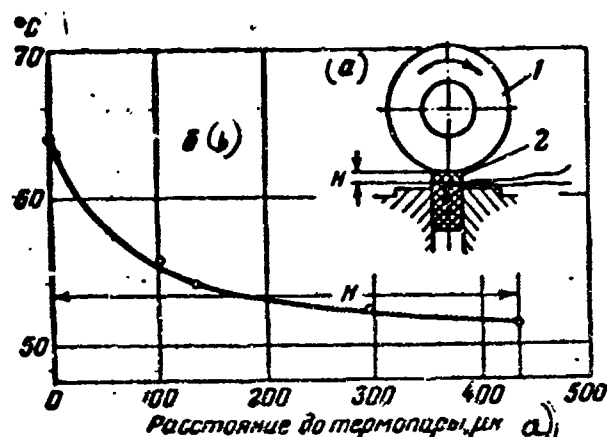
Fig. 23. Scheme of test (a) and character of temperature distribution in surface layer of capron specimen under friction conditions corresponding to beginning of adhesion of polyamide to disc (b).

a) distance to thermocouple, μ

The thermocouples were calibrated after being cemented to the specimens.

The thermocurrent was measured by a GZS-47 mirror galvanometer with scale divisions of 0.25°C.

The specimens and discs were twice rinsed with ether before the test.

The tests were run under load of 3.5 kg (unit load 17.5 kg/cm^2) and a sliding speed of 0.22 m/sec.

These conditions were so selected that an increase in the load by 0.5 kg above that selected would lead to the adhesion of polyamide to the disc in 5-10 min.

As the specimen was worn down, the hot junction of the thermocouple approached the friction surface. The thickness of the abraded layer was estimated from an indicator graduated in divisions of 1 micron. The temperature was periodically read. The test was run until the hot junction reached the friction surface. The combined wear of the specimen and the hot junction slightly increased the temperature (by 3-4°C).

After the test, lasting 16-18 hrs, an extremely thin layer of adhering polyamide was observed on the disc. The regrinding of the disc and the removal of the adhering layer did not change the temperature.

Thus on the basis of the results obtained, bearing in mind that the diameter of the hot junction of the thermocouple was 0.04-0.05 mm, it may be considered that the measured maximum temperature of 64°C corresponds to the mean temperature of a surface layer about 0.04-0.05 mm thick under friction conditions corresponding to the beginning of polyamide adhesion to the disc.

The conclusion may be drawn from these experiments that the temperature exerts a decisive influence on the character of the change of the coefficient of friction of polyamides with a change in conditions.

With rising temperature the antifriction properties of polyamides decline continuously.

Since even a relatively small change in temperature causes a considerable increase in the coefficient of friction, it may be asserted that the temperature is the most important factor determining the friction of polyamides. This proposition must be taken into account in solving problems connected with the introduction, operation and design of polyamide bearings.

At the same time, in order to improve the operating efficiency of polyamide bearings and improve their antifriction properties, one must know what properties

of the polymer (mechanical, physical or chemical) predominantly define its friction. It is also important to know the direction in which these properties should be modified.

The character of the properties of the material that determine friction is obviously closely connected with the fundamental form of interaction in friction. For this reason the establishment of the fundamental form of interaction in friction is extremely important for the solution of practical and theoretical problems of polyamide friction.

In connection with the fact that there is no clear-cut solution of this problem for polyamides, we staged a series of special experiments.

Before reporting these investigations we shall dwell on the experiments to find the effect of heat treatment on the hardness and friction of polyamides.

The effect of heat treatment on the hardness of polyamides. We noted earlier that structural changes take place during the heat treatment of polyamide. It is also known that a stay of a polymer at elevated temperatures leads to the removal of the moisture acting as a plasticizer, and that on this account it increases the rigidity and hardness of the material even in the absence of structural changes. Such a change in properties is of short duration. It disappeared after the initial moisture content is restored in the polymer, and in this connection it is not of practical significance as means of improving the properties of the material. In contrast to this, the structural changes are of long-term character (provided there is no heating of the parts during operation to temperatures exceeding the temperature of heat treatment).

Obviously, to solve the problem of the advisability of heat treatment as a means of improving the properties of polymers, it is very important to know why these properties do change during heat treatment and, accordingly, to know how long its results can persist.

In our studies we heat-treated not only materials in their original air-dried state, but also with a preliminary drying in the atmosphere at 110°C for 12 hr. A stay at this temperature could not cause appreciable structural changes.

Specimens of capron, AK-7 and P-68 were used in these experiments.

The heat treatment consisted in holding the polyamide from 7 min to 6 hr in a bath filled with oil "vapor" at 160, 190 and 220°C (the latter only for AK-7). The fluctuations of temperature were in the range of ±5°C.

To evaluate the influence of oil impregnation of the specimens on the heat treatment, some of the specimens were heated in capsules in argon by the method developed by A. P. Semenov /85/. The specimens in the capsules and without the capsules were submerged in the hot oil and removed after the heat treatment simultaneously, and were then cooled to 20°C.

Their hardness was measured on an Super-Rockwell instrument by the method developed by A. D. Kuritsina /57/.

During the study, besides comparison of the hardness of heat-treated air-dried and dry specimens, we also determined the effect on the duration of the polyamide properties of prolonged impregnation with water of the heat-tr'ed specimens of both types, and of specimens which had not been heat treated.

In this case we bore in mind that if the effect of structural changes of the polyamide on its hardness were not disclosed in connection with the elevated hardness of the specimens dried at moderate temperatures than heat treated at high temperatures, it might still be manifested in specimens containing moisture and possessing less rigidity.

The polyamides were impregnated in distilled water at 18-20°C.

Table 3 gives the hardness of the polyamides that were not heat treated. It will be seen from the table that the hardness of the specimens first dried after impregnation with water is somewhat higher than that of the specimens which were

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not first dried and were in the air-dried state until impregnation. The hardness
of the specimens of AK-7 and P-68 first dried and then impregnated with water for
600 hr continued to decrease on subsequent impregnation, while in the case of
specimens which, before being placed in water, were in the air-dry state, an
increase in the duration of impregnation had only a slight effect on the hardness,
and that only on P-68.

Table 3

State of Specimen	H, kg/mm^2		
	Capron	AK-7	P-68
Air-dry	5,7	7,0	6,8
After impregnation with water for 600 hr (air-dry before impregnation)	3,6	4,0	4,7
Same, for 1200 hr (air-dry before impregnation)	3,6	4,0	4,3
Dried at 110°C for 12 hr .... After impregnation with water for 600 hr	12,0	13,0	10,5
(dried before impregnation)	4,1	4,6	6,2
Same for 1200 hr (dried before impregnation)	4,1	4,1	5,0

This is evidence that the specimens of P-68 and AK-7 that were first dried
reach a state of saturation more slowly.

The change in the hardness of the polyamides after heat treatment for 6 hr
is shown by Fig. 24, a, b, c, and Table 4 gives its values.

It will be clear from the figures and table that the hardness of the specimens
after heat treatment was considerably greater than the hardness in the air-dried
state.

The hardness of the dried specimens after heat treatment in oil at 190 and
220°C increased slightly, and at 160°C it even declined somewhat.

The heat treatment of dried specimens in capsules filled with argon at 190
and 220°C did not increase the hardness.
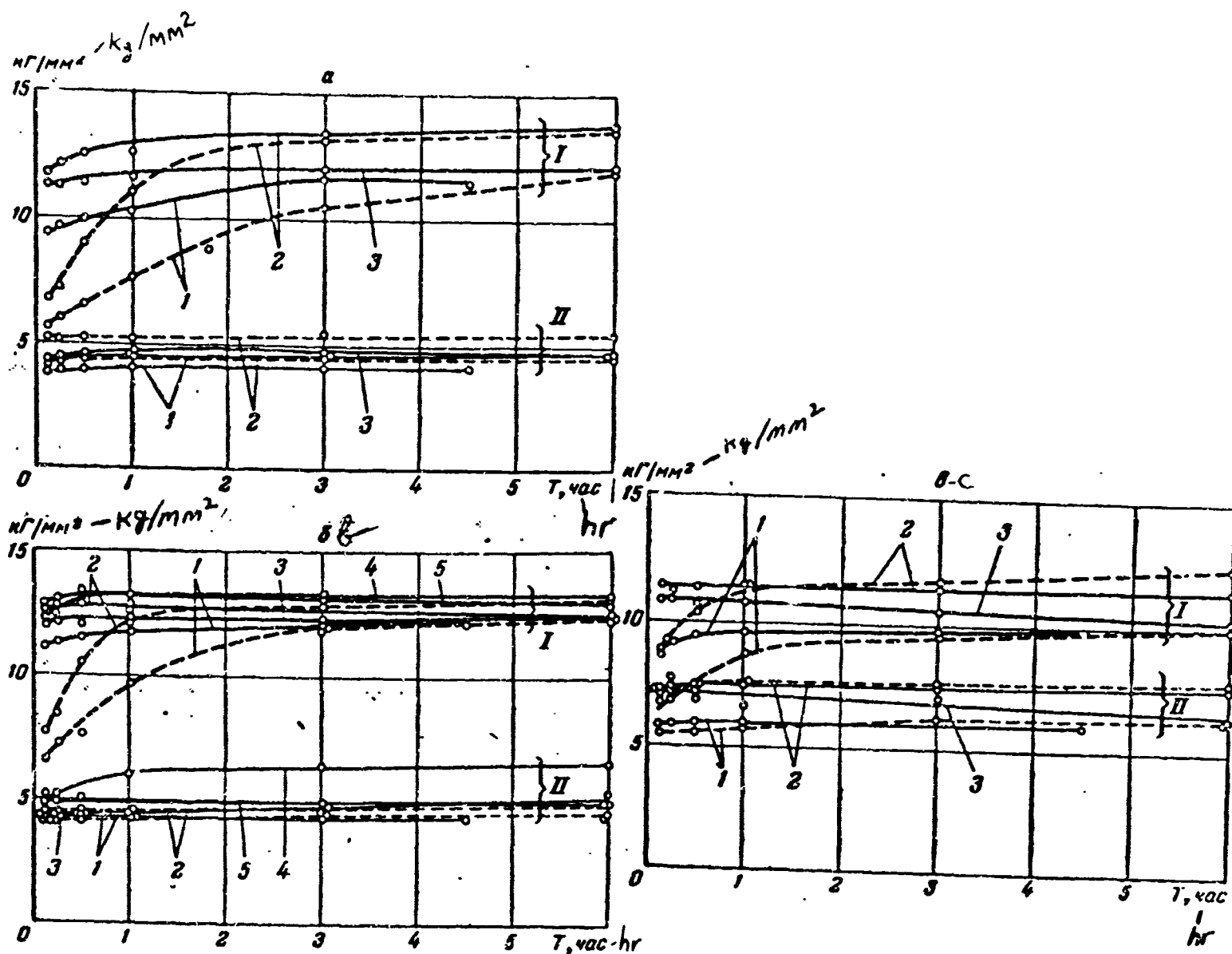
Fig. 24. Dependence of hardness of polyamides on heat treatment.

a - capron; b - AK-7; c - P-68 (specimens of polyamide before heat treatment, dry: heavy lines; air-dry: dashed lines); I - after heat treatment, dry; II - after heat treatment and impregnation in distilled water at 20°C for 600 hr. 1 - heat treatment in oil at 160°C; 2 - same, in oil at 190°C; 3 - same, in argon at 190°C; 4 - same, in oil at 220°C; 5 - same, in argon at 220°C

After saturation with water the hardness of all specimens sharply declined. There are therefore grounds for considering that the rather sharp increase of hardness as the result of heat treatment of polyamides containing moisture, for instance in the air-dried state, is due mainly to the removal of water, which acts as a plasticizer. The return of moisture to the polyamide sharply decreases the effect so obtained.

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Table 4

State of Specimen	Hardness					
	Capron		AK-7		P-68	
	kg/mm^2	%	kg/mm^2	%	kg/mm^2	%
Heat treated in oil at 160°C (air-dry before heat treatment)	12,0	210	12,4	177	10,0	147
Same at 190°C	13,6	238	13,2	188	12,4	182
Same at 160°C (before heat treatment dried at 110°C for 12 hr)	11,5	96	12,2	94	9,9	94
Same at 190°C	13,8	115	13,3	102	11,6	110
Same at 220°C	-	-	13,4	103	-	-
Heat treated in argon at 190°C (before heat treatment dried 12 hr at 110°C)	-	-	12,4	95	-	-
Same at 220°C	-	-	13,0	100	-	-

* The percentages indicate the change in hardness of the heat-treated polyamides by comparison with their hardness before the heat treatment.

In heat treatment, moisture is removed not only from the air-dried specimens, but also from those dried at a temperature lower than that of the heat treatment. The hardness of the polyamides after heat treatment for 6 hr and another impregnation with water for 600 hr is given by Table 5.

Table 5

State of Specimen	Hardness*					
	Capron		AK-7		P-68	
	kg/mm^2	%	kg/mm^2	%	kg/mm^2	%
Heat treated in oil at 160°C and impregnated with water (air-dry before heat treatment)	4,5	125	4,4	110	6,3	135
Same, at 190°C	5,5	153	4,9	125	7,9	168
Same, at 160°C (before heat treatment dried at 110°C for 12 hr) ...	4,1	100	4,3	94	6,0	97
Same, at 190°C	4,8	117	5,0	119	7,7	124
Same, at 220°C	—	—	8,5	141	—	—
Heat treated in argon at 190°C and impregnated with water (before heat treatment dried at 110°C for 12 hr)	4,6	113	4,5	99	6,5	104
Same at 220°C	—	—	5,0	109	—	—

* The percentages indicate the change in hardness of specimens heat treated and then impregnated with water by comparison with the hardness of specimens impregnated with water but not heat treated.

The smallest increase in hardness was obtained for the specimens heat-treated in argon, and the greatest for the specimens heat treated in oil. It is possible that, with the technique of investigation adopted, the increase of hardness was due to a considerable extent to the fact that after the same stay in the water the specimens which in the original state were air-dried contained more water than those first dried before impregnation, and further dried in the process of heat treatment itself, including those also impregnated with oil (cf. Table 3).

With increasing temperature and duration of the stay in oil, the saturation with oil increases. The effect of oil impregnation is particularly marked if we compare the hardness of specimens of AK-7 after heat treatment in oil and argon at 220°C.

Apparently the absorption of oil by the polyamide, hindering the further absorption of moisture, may encourage the more prolonged persistence of the elevated hardness.

The elucidation of the process and structural transformations in polyamides when heated in air to 110°C and on heat treatment in oil at higher temperatures, is a separate problem. The results indicate that the main cause of the increase in the hardness of the polyamides after heat treatment is the removal of moisture.

The irreversible structural changes and increase in crystallinity that take place under the heat treatment conditions adopted cause only an increase in polyamide hardness that is not of substantial importance for practical purposes.

The effect of heat treatment on the coefficient of friction and the limiting load for polyamides. The test was run in unlubricated friction by the scheme "shaft-partial bushing" (Fig. 5).

The load was varied over the range from 2 to 7 kg (unit load 10-35 kg/cm^2). The sliding speed was 0.22 m/sec.

Figure 25, a, b, and c, shows the curves of load dependence of the coefficient of friction during heat treatment.

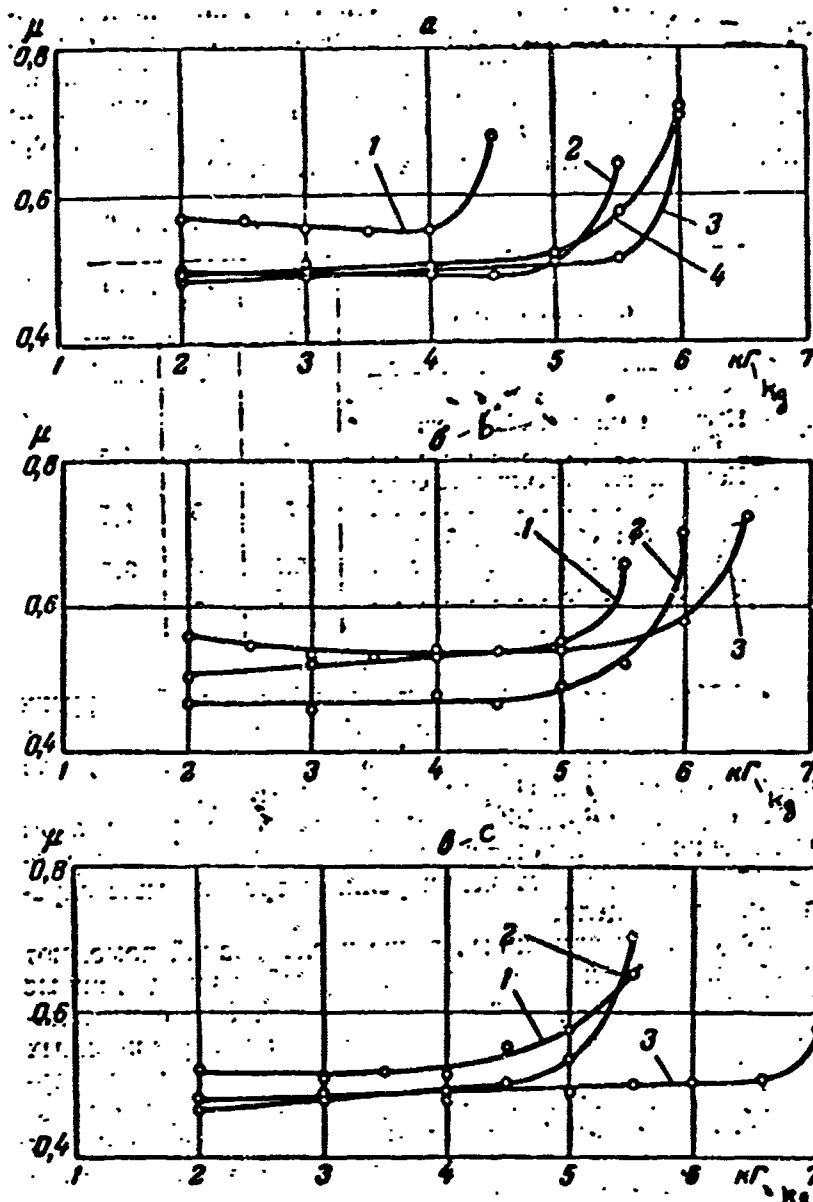Fig. 25. Load dependence of coefficient of friction of polyamides.

a - capron;   b - AK-7;   c - P-68

Specimens of capron, AK-7 and P-68 were tested. Various batches were prepared

as follows: saturation with distilled water for 600 hr at 20°C (curve 1); the same,

followed by drying in air at 110°C for 12 hr (curve 2); the same, followed by heat

treatment in "vapor" oil at 190°C for 3 hr (curve 3).

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The capron specimens were dried in air at 110°C for 12 hr and were then heat-treated in capsules in an argon atmosphere at 190°C for 3 hr (curve 4, Fig. 25, a).

The temperature fluctuations during heat treatment did not exceed ±5°C.

Each point on the graphs corresponds to the mean value of the results of three experiments.

It will be clear from the graphs that drying and heat treatment lead to a decrease in the coefficient of friction.

The saturation of the polyamide with oil during heat treatment had no effect in most of the tests on the values of the coefficients of friction.

The increase in the coefficients of friction of polyamides after saturation with water is apparently the result of an increase in the area of actual contact in friction, due to the decrease in hardness.

The critical load causing the beginning of a sharper rise in the coefficient of friction for dried and heat treated specimens is somewhat higher than for moist specimens, and the highest load values are noted for specimens heat treated in oil (Table 6).

Table 6

(1) Состояние образца	Критическая нагрузка. $P_{кр}$, кГ		
	(3) Капрон	АК—7	(4) P—68
(5) Насыщенный водой в течение 600 час при 20° С	4	5	4,5
(6) Подсушенный в течение 12 час при 110° С	5	5	4,5
(7) Термически обработанный в течение 3 час при 190°С в масле	5,5	6	6,5
(8) То же, в аргоне	5	—	—

Code:
1—state of specimen; 2—critical Load, P_{cr}, кg; 3—capron; 4—P-68; 5—saturated with water for 600 hr at 20°C; 6—dried 12 hr at 110°C; 7—heat treated 3 hr in oil at 190°C; 8—same, in argon

It will be clear from Table 6 that the critical load for specimens heat treated in oil is higher than for the dried specimens (10, 20 and 44% higher for capron, AK-7 and P-68 respectively).

This increase is evidently the result of the separation of the oil absorbed by the polyamide during heat treatment, when the friction conditions are made more severe above a certain limit.

The results of the above studies help to explain the data of other authors, given in Chapter I, which at first glance are contradictory. They indicate that it may be advisable, in order to improve the antifriction properties of polyamides, to hold them in heated oil at the highest temperatures possible, without causing destruction of the shape and dimensions of the articles, with the object of more complete absorption of oil by them. The tests have shown, however, that the effect of such treatment on the operating efficiency of polyamide bushings is small.

The results have also shown that the change in the hardness of polyamides after heat treatment is due mainly to moisture removal and, although saturation with oil during heat treatment favors the more prolonged maintenance of the elevated hardness, the effectiveness of this means of changing the properties of the polymer is slight, since, during operation, as the initial moisture content is restored to the polymer, the disappearance of the original results is inevitable.

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CHAPTER IV

FINDING THE PRIMARY FORM OF INTERACTION IN FRICTION OF A

POLYAMIDE-STEEL PAIR

In developing the method of study we bore in mind that in finding the primary
form of interaction a comparison of the changes in the coefficients of friction in
the mechanical properties of the polymers might be helpful. For mechanical inter-
action, one should observe a connection in the changes of these characteristics.
But the change in the frictional force might also be related to the change in the
mechanical properties in the case of molecular interaction as well. In the latter
case the connection is due to the dependence of the area of actual contact on the
mechanical properties.

For this reason the existence of a correspondence between the change in the
coefficient of friction and the mechanical properties is by itself still

insufficient to warrant a judgment as to the primary form of interaction. The absence of such correspondence, however, would indicate that it is not the mechanical properties that primarily determine the value of the frictional force and, consequently, that the nonmechanical interaction is the primary form. In this latter case (since we are discussing only the mechanical and molecular interactions in friction) the experiments would support the hypothesis of molecular interaction between the wearing surfaces.

A comparison of the relationships between the variation of the mechanical properties and the coefficients of friction thus appears advisable for a number of materials known to possess a sharply differing capability for molecular interaction. In connection with the existence of a sharp temperature dependence of the coefficient of friction in the polyamides, the variation of their temperature was adopted as a means of modifying the properties of the polymers.

In addition to the polyamides, we selected a number of linear polymers with different intramolecular bonds and intramolecular cohesion: low-pressure (LP) polyethylene and polytetrafluoroethylene.

A substantial peculiarity of the polyamides, as already noted, is the existence of polar groups and hydrogen bonds between the molecules, sharply increasing the energy of their molecular cohesion.

The molecule of polyethylene, according to present ideas, consists of a chain mostly consisting of hydrocarbon groups, CH_2. The intermolecular bonds are of disperse character. The energy of their molecular cohesion is substantially lower.

Polytetrafluoroethylene is likewise marked by the disperse character of the intermolecular bonds, the interaction with other atoms being weakened by the shielding action of the fluorine atoms. It is precisely for this reason that of the known polymers, polytetrafluoroethylene has the smallest adhesive power.

The effect of temperature on the coefficient of friction of LP polyethylene and polytetrafluoroethylen. The temperature dependence of the coefficient of

friction of LP polyethylene and of polytetrafluoroethylene was determined by the same methods used for the polyamides. In this method, owing to the insignificant differences in the thermal conductivity coefficients of the test materials, the temperature and character of its distribution in the surface layer should be close together.

It will be seen from Fig. 26 that the coefficient of friction of LP polyethylene increases less sharply with increasing temperature than it does in the polyamides, and that the coefficients of friction of polytetrafluoroethylene declines with rising temperature.

The results indicate that the character of variation of the coefficient of friction with increasing temperature is not the same for different polymers.

The influence of temperature on the hardness of polymers. The heatable stage and indentor described in Chapter III were used to measure the hardness at various temperatures.

The hardness was measured on a Super-Rockwell instrument, by the method developed by A. S. Kuritsina /57/.

The temperature was measured by a thermocouple of wire 0.1 mm in diameter. The hot junction was cemented into the test specimens to a depth of 1 mm and at a distance of 6-7 mm from the site of indentation. The cement used in making up the hot junctions of the thermocouples was a solution of polyamide in a 10-15% aqueous solution of phenol.

Before the test the specimens and indentor were heated and held at constant temperature for 20-25 min.

The mean values of the hardness and its decline, in %, with increasing temperature are given in Table 7 (the hardness at $25^{o}C$ was taken as 100%).

As will be seen from the table, the character of variation of hardness was the same for all polymers tested.
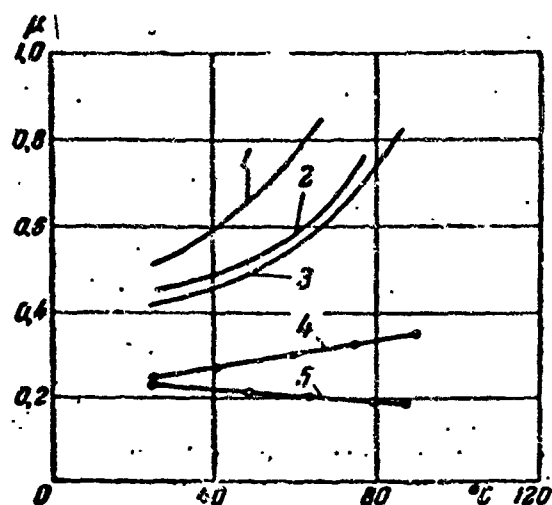
Fig. 26. Temperature dependence of coefficient of friction of polymers.

1 - capron; 2 - P-68; 3 - AK-7; 4 - LP polyethylene; 5 - polytetrafluoro-ethylene.

Table 7

Temperature, °C	Hardness					
	Capron		LP Polyethylene		Polytetrafluoroethylene	
	kg/mm^2	%	kg/mm^2	%	kg/mm^2	%
25	8.45	100	3.35	100	3.2	100
60	v.5	53.4	1.83	56	2.0	62.5
90	3.9	46.2	1.13	35.5	1.45	45.2

Effect of temperature on the shear resistance of polymers. Tests were run by the aid of a specially designed appliance on a universal tensile tester with a dynamometer scale division of 0.1 kg.

Loading was at the rate of 180 kg/min continuously to complete rupture. The cross-section of the specimens was 2 x 2.3 mm.

Before the test the apparatus with the specimens was held at constant temperature for not less than 25 min.

The shear resistance was calculated by dividing the maximum load by twice the cross-section of the specimen.

Table 8 shows the mean values of the shear resistance and of its decrease in % with increasing temperature (taking the shear resistance at 25°C as 100%).

Table 8

(1) Температура, °C	(2) Сопротивление срезу					
	(3) капрон		(4) полиэтилен НД		(5) политетрафтор-этилен	
	(6) кг/мм²	%	кг/мм²	%	кг/мм²	%
25	10,25	100	4,9	100	3,2	100
50	8,05	78,5	3,93	80	2,65	83
90	6,95	67,8	2,42	49,5	2,58	80

Code:
1-Temperature; 2-Shear resistance;
3-Capron: 4-LP Polyethylene;
5-Polytetrafluoroethylene; 6-kg/mm²

As shown by the table, the character of the variation of shear resistance is likewise the same in all polymers tested.

The sharply different character of the variation of the coefficient of friction with increasing temperature (Fig. 26), with the character of the variation of the mechanical properties (hardness and shear resistance) very similar in all cases, gives grounds for concluding that the variation of the coefficient of friction is not determined in all the polymers tested by the variation of the mechanical properties.

The greatest difference in the character of the variation of the coefficient of friction is observed in polytetrafluoroethylene, which has the lowest molecular cohesion, and in polyamide, whose molecular cohesion is the greatest of all the polymers tested.

It is natural to assume that the molecular interaction in the friction of the polyamide is manifested more distinctly and it is precisely this, causing the difference in the corresponding relationships in polytetrafluoroethylene and polyethylene, that determine the character of the temperature dependence of the coefficient of friction.

It is also clear from Table 7 that LP polyethylene has essentially a greater decline in hardness with increasing temperature than polyamide.

Obviously during friction under the same temperature rise under the same other conditions, a greater increase in the area of actual contact should be observed with rising temperature in LP polyethylene than in polyamide. For this reason the divergence between the coefficient of friction of polyamide and that of LP polyethylene, increasing steadily with rising temperature, may be explained, not by the greater increase in the area of actual contact (since the opposite should in fact take place) but by the peculiar character of the variation of interaction in the friction of polyamide.

Consequently these results suggest that such a sharp increase in the coefficients of friction of polyamide with increasing temperature is due to the peculiarities of their chemical composition and structure and, in particular, to the presence of polar groups, which are absent from LP polyethylene, and the ability to form hydrogen bonds.

Comparison of the variation of the coefficient of friction and of the ratio between shear resistance and hardness (S/H) of polyamide with rising temperature. Additional information on the basic form of interaction during friction of polyamides may be obtained from a comparison of the ratio between shear resistance and hardness with the coefficient of friction on temperature variation. In accordance with the Boden-Tabor adhesion theory, a certain ratio between these quantities should be observed during unlubricated friction.

Figure 27 shows the corresponding relations for capron. It will be seen from the figure that the character of variation of these quantities is different. It must be borne in mind that the ratio S/H is obtained as a function of the actual temperatures of the polymer. The curve for μ, on the other hand, is plotted against the temperature measured at a distance of 1 mm from the friction surface.
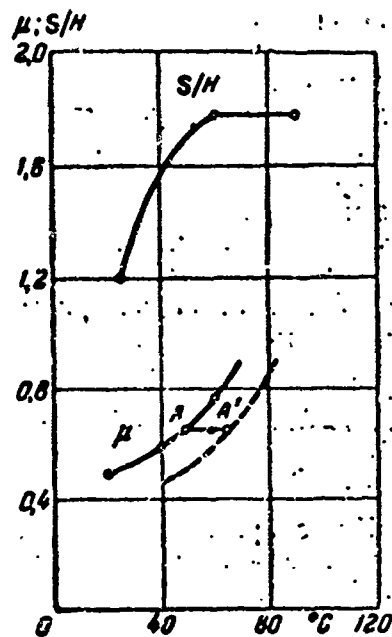
Fig. 27. Temperature dependence of coefficient of friction of capron and of ratio between shear resistance and hardness.

The results obtained in Chapter III permit us to make certain remarks about the true position of the curve of the coefficient of friction obtained with rising temperature. Since the temperature of the specimens in these experiments was measured at a distance of 1 mm from the friction surface, the actual temperature

Fig. 28. Load dependence of frictional force in test of combined specimens on the scheme "sphere-plane."

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on the friction surface itself was higher.

At an average temperature of 49°C, the polyamide adhered to the disc (Fig. 16). But the adhesion of capron begins only at a surface layer temperature of 64°C (Fig. 23). The drop between the temperature of the surface layer and the temperature measured at a distance of 1 mm from the surface is 15°C.

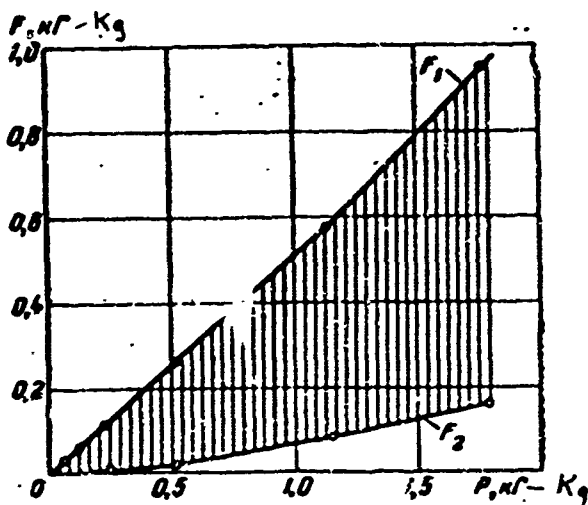On this basis we may conclude that the true curve of the temperature dependence of the coefficient of friction of capron should be shifted to the right relative to the curve shown by Fig. 27, so that its point $\underline{A}$ (corresponding to the beginning of adhesion of polymer to the disc) is shifted to the right by not less than 15°C, and will lie to the right of point $\underline{A}'$.

According to the adhesion theory, $\mu = S/H$ should be true in cases where the shear takes place in depth in the softer material. The lack of agreement between these quantities and the existence of the inequality $\mu \neq S/H$ (Fig. 27) is evidence that at different temperatures a bond of different strength is formed (with the shear resistance less than the bulk shear resistance), i.e., the shearing of bonds takes place between the surfaces, instead of in the interior of the polyamide.

The variation of the coefficient of friction under these conditions may be due primarily to the variation of the forces of surface interaction.

Thus these results speak for the view that the friction of polyamide against steel without lubrication is determined primarily by the molecular interaction between the surfaces of these bodies. To determine the extent to which this cause affects the behavior of polyamide in lubricated friction, we ran additional experiments.

Study of the effect of temperature on the coefficient of friction of polyamides with lubrication by oils containing polar additives was conducted under the same conditions as with lubrication by industrial oils. The industrial oils "12" and "45" were used as the lubricants, with 1% of oleic acid as the additive.

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With this experimental method, the beginning of the rise of the coefficient of friction with lubrication by industrial oil "12" with additives corresponds to a temperature of 130°C (Fig. 19, curve 2); and to 145°C with lubrication by industrial oil "45" (Fig. 20, curve 2). The regions of rise of the coefficient of friction correspond to a considerable softening of the surface layer of polyamide, and the regions of decline to its melting.

The melting of the surface layer and its attainment of the temperature 215°C, accompanied by a rapid failure of the capron specimen, occurred at an average temperature of 160°C, measured at a distance of 1 mm from the friction surface. The temperature drop was 215-160 = 55°C.

Assuming roughly that at the measured temperatures of 130 and 145°C the drop was the same or somewhat smaller (the rate of temperature rise was held the same in all the experiments) and amounted to 45-55°C, we get the result that the critical temperatures are of the order of 175-185°C for industrial oil "45" with the additive and 190-200°C for industrial oil "12" with the same additive. It will thus be clear that the introduction of a polar additive helps to prevent an increase in the coefficient of friction of polyamide practically throughout the temperature range of its operation.

The addition of a polar additive prevented the increase of the coefficient of friction. This proves that the rise in the coefficient of friction of polyamide with temperature during lubrication by industrial oils without a polar additive was due to intensification of molecular interaction between the friction surfaces.

Study of the features of interaction in the friction of a polyamide-steel pair. Our experiments here consisted essentially in determining that component of the force of friction that is due to molecular interaction in unlubricated friction, and in the estimation of the shear resistance of the bonds so formed.

To solve this problem requires a separate quantitative evaluation of the molecular and mechanical components of the force of friction and the measurement of the area of actual contact.

Bowden, Moore and Tabor evaluated the adhesion and transverse components on displacement over an indium surface of slides in the form of vanes, hemispheres and hemicylinders of the same radius.

The plasticity of indium assured the preservation of the friction track and made it possible to measure it subsequently. Those authors assumed that the difference in the tractive force on displacement of the vane and the cylinder at the same track width was due to the adhesional component. The shear resistance was found by dividing the adhesive component by the lateral surface of the cylinder submerged in the indium.

Since the true elastic base of polyamide makes it impossible to preserve the trace on the friction surface from which the area of actual contact could be estimated, a different method was worked out. The friction of a steel ball on the plane surface of a combined specimen with a plastic base and an extremely thin layer of polyamide on the surface was estimated. In view of the negligible resistance to deformation by a thin film of polyamide (of the order of 1 micron thickness), it may be considered that the mechanical component of the frictional force is due exclusively to the deformation of the plastic base. By artificially minimizing the molecular interaction, the value of the mechanical component may be brought close to the value of the total frictional force, and that force can then be roughly estimated (provided constant width of the track and constant uplift in front of the slide can be maintained). The difference between the frictional force determined before and after the artificial depression of molecular interaction will give the value of the molecular component.

Evaluating the area of actual contact from the track remaining in the plastic base we may calculate the shear resistance of the bonds formed between the friction surfaces on account of molecular interaction.

The base of the flat specimen was prepared from lead, which is almost of the same hardness as polyamide. This permits the assumption that there will be no

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substantial differences in the areas of actual contact obtained on bonded specimens from those on all-polyamide specimens.

The specimens were prepared as follows: on lead plates 8 x 30 x 4 mm, surfaces of 8 x 30 mm were given a high degree of smoothness by pressure of the plate in contact with the polished surface of a measuring plate.

After degreasing in ether, films of two types were applied: (1) capron, 1 micron thick, in a solution of capron in 85% formic acid; (2) FBF-74 varnish and oleic acid (a 3% solution of oleic acid in aviation gasoline). The application of the films of FBF-74 polytetrafluoroethylene varnish and oleic acid lowered the molecular interaction on specimens with a lead base.

Before the experiments the specimen coated with capron films were twice washed with ether. The steel specimens, which consisted of hardened balls of ShKh15 steel, 6 mm in diameter, were wiped off with silica gel and washed twice with ether.

The experiments were run with reciprocating motion of the specimens on the apparatus described in Chapter II (Fig. 9).

The sliding speed used was 0.000003 m/sec, so that there was no frictional heating of the specimens. The load on the ball was increased from 0.126 to 1.755 kg in stages spaced 7-8 min apart. On each stage the constant frictional force was maintained for not less than 5 min. With increasing test time by a factor of 5-6 or more, the frictional force did not vary.

The load dependence of the frictional force for specimens coated with films of FBF-74 varnish with oleic acid (F_2), and for specimens coated with capron films (F_1) is shown in Fig. 28. Each point is plotted from the result of not less than three tests. The arrangement of the specimens is shown in Fig. 29. The principal characteristics obtained in these tests are shown by Tables 9 and 10.

The slight differences in the width of the friction track and the uplift in the front part of the track in specimens of both types at the same load gives grounds from the conclusion that the losses due to deformation of the base, i.e.,

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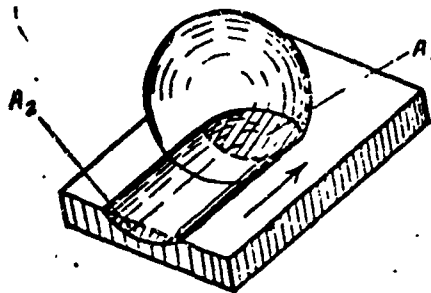
Fig. 29. Arrangement of specimens in friction for tests on scheme "sphere-plane":
1 - steel ball 2- flat specimen; A_1 - half of surface of spherical segment; A_2 - area of circular segment.

the mechanical component of the frictional Force, F_{mech}, is about the same in both cases. It will be seen from Table 9 that the value for F_2 is approximately porportional to the cross-sectional area of the track A_2, which is equal to the area of a circular segment. The factor of proportionality k_2, representing the resistance of the lead base to deformation, varies in the range $k_2 = 3$ to 3.74 kg/mm^2, which is close to the hardness of lead.

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Table 9

Parameters	Load, kg				
	0.126	0.252	0.505	1.130	1.755
Frictional force F_2, kg	0.0037	0.009	0.025	0.083	0.161
Width of friction track b, mm	-	0.45	0.65	0.88	1.10
Area of spherical segment A_2, mm^2	-	0.003	0.008	0.023	0.043
Resistance of lead base to deformation, $k_2 = \frac{F_2}{A_2}$, kg/mm^2	-	3.0	3.13	3.61	3.74

Table 10

Parameters	Load, kg				
	0.126	0.252	0.505	1.130	1.755
Total frictional force F_1, kg	0.063	0.128	0.260	0.575	0.945
$F_1 - F_2 \sim F_{mol}$, kg	0.059	0.119	0.235	0.492	0.784
Width of friction track b, mm	-	0.43	0.63	0.93	1.19
Half surface of spherical segment A_1, mm^2	-	0.085	0.169	0.330	0.527
Shear resistance of bonds, $k_1 = \frac{F_1 - F_2}{A_1}$, kg/mm^2	-	1.4	1.39	1.49	1.49
Share of molecular component, F_{mol}, %	93.7	93.0	90.5	85.5	83.0

The molecular component of the frictional force ($F_{mol} = F_1 - F_2$) proved in fact to be proportional to half of the surface of the spherical segment A_1, which was to be expected. The proportionality factor k_1 representing the shear resistance of the bonds formed between the contacting surfaces on variation of load, varies but slightly ($k_1 = 1.39 - 1.49$ kg/mm^2). The fact that it is only about 1/7 as great as the bulk shear resistance of the polymer (at 22°C, $\underline{S}$ for capron is 10.3 kg/mm^2), is another proof that the shear of the bonds takes place between the friction surfaces and has no direct connection with the mechanical properties of the polymer.

The increasing share of the molecular component with decreasing load is connected with the fact that at small loads the depression of the spherical specimen

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The increasing share of the molecular component with decreasing load is connected with the fact that at small loads the depression of the spherical specimen

is less and the relative size of the surface of the spherical segment is greater.

In this connection we may assume that, on a base harder than lead, in particular on an all-polyamide specimen, when the submergence of the slide will be somewhat less, the share of the molecular component should be not lower than that here determined.

In spite of the closeness of the results obtained, we may conclude that the molecular component in friction of steel against polyamide not only determines the character of the variation of the frictional force with varying conditions of friction, as already shown, but may also predominate in the total frictional force.

Moreover, the sharp difference in the force of surface interaction in the experiments described by curves F_1 and F_2 (Fig. 28), with the slight difference in the width of the friction tracks, and in the heights of the uplifts, indicates that the surface molecular interaction may directly determine the values of frictional force.

The absence of disruption of the polymer films after passage of the slide in most experiments is evidence that during friction surface interaction took place only between the steel sphere and the polymer.

At loads of 1.755 kg, however, the capron film did show considerable thinning in places, and the lead base partially emerged to the friction surface. The frictional force increased somewhat. The surface layer of the track began in some places to be displaced, and small corrugations appeared. The ball rose and slid over them, and the cycle then repeated.

The frictional force fluctuated continuously. The width of the track was somewhat greater (by about 10%) than that of the tracks formed on specimens coated with FBF-74 varnish and oleic acid.

Thus in those cases when the surface interaction increased to beyond a certain value, apparently connected with the resistance of the surface layers of the softer

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material to deformation, the increase in the frictional force was partially due to the formation of a wave or corrugation in front of the slide and to the increase in the mechanical component of the frictional force connected with this corrugation.

The study described in this chapter has shown that the peculiarity of polyamide behavior in friction without lubrication against steel are due to the peculiarities in the character of variation of molecular interaction between the contact surfaces.

In friction under conditions of boundary lubrication, when it is insufficient to prevent the direct contact of the surfaces, the molecular interaction between the polyamide as in steel pair may likewise to a considerable degree determine the values of friction. This appeared most distinctly with a lubricant not containing polar additives, with rising temperature.

The disruption of the hydrodynamic lubrication and the appearance of direct interaction between the surfaces takes place on attainment of the critical conditions of bearing operation. The further serviceability of the friction unit depends primarily on the properties of the materials of the pair.

We may conclude from these experiments that molecular interaction is the second major factor determining the friction of polyamides.
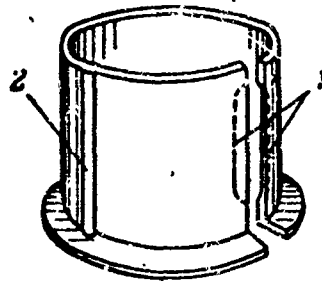
Fig. 30. Cast polyamide bushings.

CHAPTER V

STUDY OF THE FRICTION OF POLYAMIDE BUSHINGS

To study the operation of bushings, stand tests * were performed on cast-iron
(capron spray-coated) and cast capron bushings.

The bushings were 40 mm in diameter and 50 mm long. A thin layer of polyamide
was applied to the cast iron bushings by the vortex spray method, using the
technique developed and used at the Plastics Laboratory, ENIMS. After grinding,
the thickness of the layer was 0.20 mm. The surface finish corresponded to $\nabla 6-\nabla 7$.
The clearance used was 0.06 mm (X fit); 0.12 mm (X_3 rit); and 0.20 mm. The
tolerance for the clearance was ± 0.01 mm.

The cast bushings of wall thickness 1.5 mm were cast at the Physicochemical
Technology shop of the Moscow Automobile Plant imeni Likhachev (Fig. 30). In the
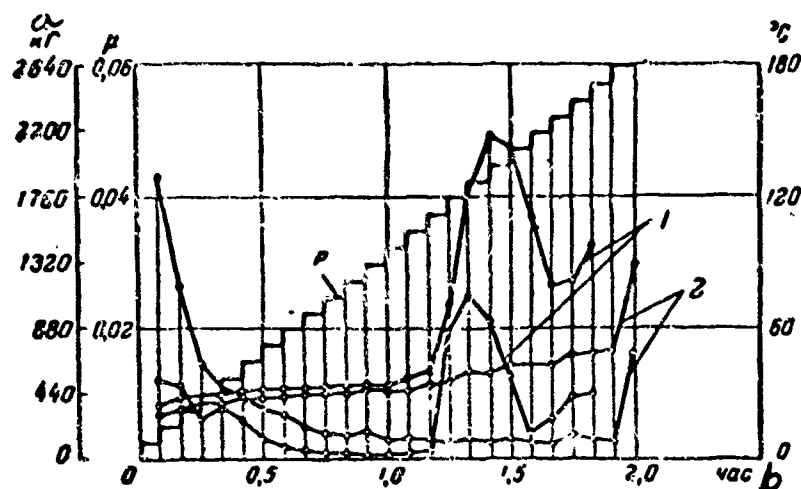
Fig. 31. Load dependence of coefficient of friction and temperature of polyamide bushings (clearance 0.06 mm):

1 — capron;   2 — OTsS 6-6-3 bronze

a — kg;   b) hr

nonoperating part the bushings were slotted and the oil collecting chamfers 1 were cut into the edges. This cutting provided space for thermal expansion at minimum variation of the initial clearance. The bushings were freely inserted in the clips. They were prevented from turning by the pin 2 fitting into the groove of the clip. The working surface was not machined. The clearance was 0.20-0.25 mm.

For comparison we also tested bushings of OTsS 6-6-3 bronze, which is widely used as an antifriction material. They did not differ in dimensions and design from the finished capron faced bushings. The surface finish was ∇ 7- ∇ 8; the clearance was 0.06 ± 0.01 mm (Fig. 11). In connection with the fact that the apparatus for measuring the frictional force takes the friction of the bushing against the shaft * and the two rocker bearings 3, a special calibration was run to determine the friction loss in the latter. For this purpose, instead of the test bushing two ball bearings (likewise transverse bearings) were placed instead of the test bushing and the friction of the four bearings was determined at various loads and at the rpm selected for the main experiments. The correction so determined (related to the two ball bearings) were introduced into the calculations for the frictional force of the bearings of the main experiments.

The temperature of the bushings was measured by a chromel-alumel thermocouple with wires 0.2 mm in diameter. Its hot junction was placed in the operating part of the bushing in the middle of its length at a distance of 2 mm from the friction surface.

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Before the test the shaft and bushings were washed with gasoli e. The load was increased at intervals of 15 min by stages to 110 kg, until the sharp rise in the coefficient of friction began. The sliding speed was 1.3 m/sec.

To check the influence of the time interval between the successive loads, tests were made in which the load was increased at 5 min and at 30 min intervals. They showed that in the limits investigated, the length of the interval between application of the additional loads has no effect on the results.

In all experiments, the lubricant used was industrial oil "12." The tests were run in two variants of lubrication: (1) abundant lubrication, continuously fed to the friction zone at the rate of 3.6 liter/hr; (2) insufficient lubrication fed at the rate of three drops every 15 min.

The tests with abundant lubrication were run on bushings faced with a thin capron layer (clearance 0.06, 0.12 and 0.20 mm) and on VTsS 6-6-3 bronze bushings at 0.06 mm clearance.

The period of sharp increase of frictional force in the bronze bushings was accompanied by adhesion of bronze to the shaft and seizing of the friction surface.

The limiting loads marking the beginning of the rise in the frictional force in the test of the three bronze bushings were as follows:

	1	2	3
Total	2640	2880	2750
	132	143	137.5
Unit value			

On the basis of the experiments, the average total load was 2750 kg and the average unit load was 137.5 kg/cm^2.

In testing the capron-faced bushings, the load was brought up to the same level. In the bushings with clearance 0.06 mm, at a load above 1000-1500 kg, the coefficient of friction and the temperature both increased, but then decreased after 15-20 min. The bushings continued to operate.

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The load dependence of the coefficient of friction and at the temperature of one of these tests is shown by Fig. 31 (curves 1). We also show, for purposes of comparison, the results of OTsS 6-6-3 bronze bushings, whose coefficient of friction and temperature vary smoothly up to their sharp rise on seizing (curves 2).
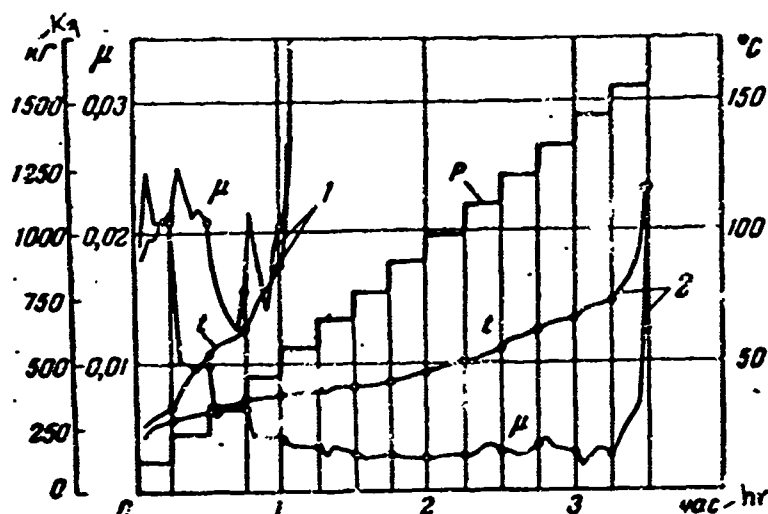

Fig. 32. Load dependence of coefficient of friction and temperature of bushings with insufficient lubrication (clearance 0.12 mm).

After the test the friction surface of the capron-faced bearing had a polished appearance; no traces of machining persisted. At the edge of the lubricating furrow, light beading was noted, indicating that there had been a melting of the layer during the test. Since the clearance was small (0.06 mm), the conditions of normal lubrication were apparently disturbed, and the temperature rose sharply (Fig. 31). The melting of the layer and the displacement of the melted polyamide into the cavity of the lubrication groove then took place. The clearance increased, the operating conditions of the bearing improved, and as a result the coefficient of friction and the temperature both declined.

In the bushings with a clearance of 0.12 mm, at loads over 1200-1500 kg, a period of unstable operation began, and brief rises in the coefficient of friction and the temperature were observed.

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At the same time, after the end of the tests, except for a light crushing and smoothing of the ridges (left by the machining), no damage of the friction surface visible to the naked eye could be detected.

Apparently the brief rises in the coefficient of friction and temperature were connected with the disturbance of the normal conditions of lubrication and the melting of polyamide on extremely minute regions of the rough projections.

Under critical conditions, when the supply of lubricant to individual regions of the friction surface is hindered, a heating and melting of the surface layer was observed in the capron bushings.

After melting of the layer and increase of the clearance, the operating conditions of the bushings improved, since the conditions for the lubricant feed improved. No seizing of the friction surfaces was noted.

The tests under insufficient lubrication were run on cast-iron bushings faced with a thin layer of capron 0.2 mm thick, and on cast capron bushings of wall thickness 1.5 mm. For comparison, bushings of OTsS 6-6-3 were also tested.

Cast iron bushings. To prevent disturbance of normal operation of the bushings, a clearance of 0.2 mm was adopted. After washing in aviation gasoline and drying the shafts and bushings, the same quantity of lubricant was applied to their working surfaces and was uniformly distributed there (two drops on the shaft and three drops on the bushing). Then, at intervals of 15 min, before increasing the load, a new portion of lubricant (three drops) was fed.

Three specimens were tested. The numerical values of the limit loads and temperatures are given in Table 11.

Figure 32 shows the load dependence of the coefficient of friction and of the temperature of the bushings. The coefficient of friction in the temperature of the capron-faced bushings (curve 1) proved to be considerably higher, and the limit load considerably lower for insufficient lubrication than those of the bronze bushings (curve 2).
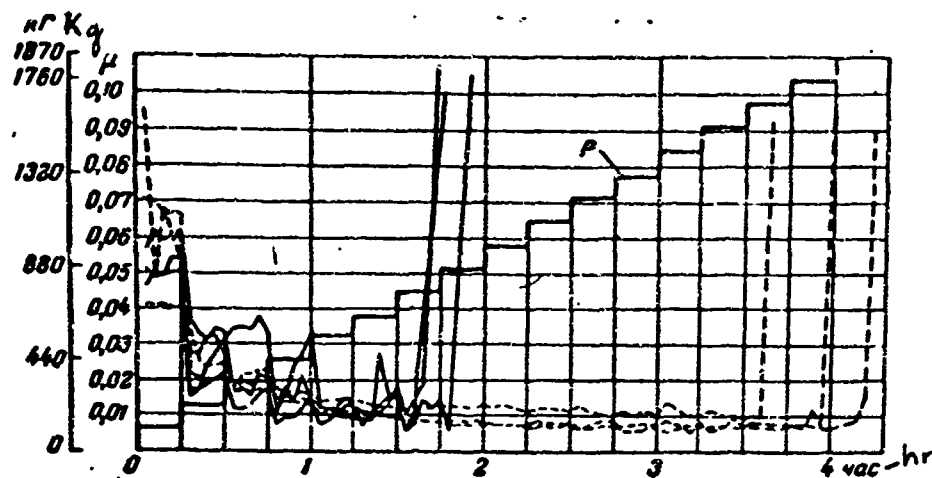
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Fig. 33. Load dependence of coefficient of friction of cast capron bushings.

Table 11

Material of Bushing	Specimen 1		Specimen 2		Specimen 3		Average	
	P_{lim}, kg	T, °C	P_{lim}, kg	T, °C	P_{lim}, kg	T, °C	P_{lim}, kg	T, °C
Capron facing OTsS 6-6-3	500	134	220	124	660	120	477	126
bronze	1540	118	1210	146	1760	112	1503	125

After reaching the melting point, there is a continuous abrasion of the layer, with transport of the melted particles of capron to the inlet side of the bushing.

If the temperature failed by 10-15°C to reach the melting point of capron, the bushings showed no defect nor traces of wear. They completely preserved the scratches from the machining.

In all cases the capron bushings went out of commission after heating of the surface layer to the melting point. In view of the limited lubrication in these experiments the melting of the surface did not lead to improvement of bushing operation.

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In connection with the slight differences of the conditions of lubrication in different experiments, the melting point of capron was reached by the surface layer and the bushings went out of commission at substantially different loads. The difference between the measured temperatures, however, was small.

The cast capron bushings were tested by the same method. At a sliding speed of 1.3 m/sec under a load of 110 kg, the bushings went out of commission 5-10 min after the beginning of the test. The sliding speed was then lowered to 0.67 m/sec.

Figure 33 gives the load dependence of the coefficient of friction of the capron bushings. The heavy lines show the rise in the coefficient of friction of cast capron bushings with lubrication by industrial oil "12," and the dashed lines show the same with lubrication by industrial oil "12" with 1% oleic acid added.

In the intervals between the regular feeding of oil, when the layer of oil became thin, periodic increases in the coefficient of friction were noted. When the load increased above a certain level, there was a sharp rise in the coefficient of friction.

As in the last case, it was accompanied by a melting of the surface, after which the friction declined somewhat. On the surface of the shaft the layer of polyamide spread in the form of a continuous film.

In these tests, as in the last ones, the capron bushing went out of commission under critical conditions only as a result of the melting of the surface layer. We have shown above that the temperature is a major factor determining the friction of polyamide, owing to the fact, characteristic of polyamides, that there is a sharp temperature dependence of the coefficient of friction and a continuous decline in their antifrictional properties with rising temperature.

The tests described in this chapter not only confirm this but also shows that the extreme temperature level that can be reached under operating conditions of bushings determines their serviceability.

Indeed, in operation with abundant lubricant, when the heating caused by melting is excluded, the serviceability of bushings faced with capron proved to be no lower than that of bronze OTsS 6-6-3 bushings. When the lubrication did not provide a reliable separation between the capron and steel surfaces (owing to insufficient lubrication or insufficient clearance), the coefficient of friction and the temperature increased rapidly, and the bushings went out of commission at loads only a third as great as for OTsS 6-6-3 bronze under the same conditions. With decreasing heat removal from the friction surface using bushings with a wall thickness of 1.5 mm, the bushings went out of commission under conditions even less severe.

The behavior of a polyamide bearing and its serviceability are determined by a number of factors: the severity of the operating conditions (the load and sliding speed), the quantity and quality of the lubricant supplied, the heat removal from the friction surfaces, the design, etc.

In most cases today there is no method of objective and quantitative evaluation of the influence of these parameters on the behavior of antifriction

material in a friction unit. For this reason, to elucidate the possibility of
using plastic in some specific friction unit, one must run prolonged tests under
operating conditions. Here, even such tests cannot answer the question as to the
margin of reliability with which a polymer can be used. Evidently only the
estimation of the maximum temperature that can be reached under actual production
conditions, of a given unit or similar units, can answer this question quickly
enough. In other words, the maximum temperature level that can be reached in some
specific friction unit may be a reliable criterion for judging the possibility of
using polyamides in such unit. It is obviously advisable to use this criterion in
solving problems on the introduction of polyamides into machines and mechanisms now
in operation.

The experiments have shown that with oil lubrication the operation of polyamide
bushings can be continued up to the temperature of considerable softening and melt-
ing of the polymer. But a considerable decrease in the mechanical properties, the
sharp rise of creep and the decrease in the wear resistance of the polymer takes
place at even lower temperatures. The maximum allowable temperature should thus
be determined by a group of properties, including not only the coefficient of
friction but also the wear resistance, ability to flow under load, etc. Naturally
with such an approach to the choice of the extreme temperature, that temperature
will be affected not only by the character of the variation of the physicomechanical
and chemical properties of the polymer, but also by the design of the bearing, and
by the severity of the specifications that its operating properties must meet.

The effect of a polar-active additive to the mineral oil on the serviceability
of polyamide bushings. It follows from the above that the force of friction of
polyamide on steel increases with temperature as a result of the peculiar character
of the variation of molecular interaction. This is manifested in both unlubricated
friction and in friction lubricated with mineral oil. The introduction of a polar-
active additive, which decreases molecular interaction, prevents this rise until

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the polyamide reaches a temperature in which considerable softening takes place.

A decrease in molecular interaction should apparently increase the serviceability of bearings, since friction, heat liberation and temperature are all decreased. Cast capron bushings were tested to verify this proposition.

The technique was the same as that used in the earlier test. The lubricant used was industrial oil "12" with 1% of oleic acid added. The sliding speed was 0.67 m/sec. The load was increased every 15 min in steps of 110 kg until a sharp rise in the coefficient of friction. A melting of the surface was observed, followed by a decrease of the coefficient of friction, and the bushings went out of commission.

In contrast to the preceding case, there was almost no rise of the coefficient of friction in the intervals between successive applications of lubricant. This indicates that the operation of the bushings is more stable, and the coefficient of friction lower. The extreme loads were increased by an average factor of 2.3.

Thus the weakening of the molecular interaction leads not only to a decrease in the coefficient of friction but also to an increase in the serviceability of capron bearings.

Fig. 34. Principal forms of capron bushings.

CHAPTER VI

TESTS OF CAPRON BUSHINGS INSTALLED IN METAL-CUTTING MACHINE TOOLS

Estimate of extreme temperatures. The experiments described in the preceding chapters indicate that, owing to the peculiarities of the chemical composition and structure of polyamides, their friction on steel increases with decreasing temperature. At the same time, under favorable conditions (good heat removal, good lubrication, etc.), the serviceability of polyamide bushings is not inferior to that of bushings of the widely used OTsS 6-6-3 bronze.

To test the operation of capron bushings under industrial conditions, they were installed in the metal-cutting machine tool 1K62. This machine tool was selected because it is the most widely used lathe and screw-cutting machine of medium power (N_g = 10 KW).

On the basis of our earlier conclusions, and to accelerate the solution of the problem, we estimated the maximum temperature of capron bearings under service conditions. *

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Bushings of cord capron were installed instead of roller and ball bearings and bronze bushings in the mechanisms of the speed box, the feed box and the apron. For the most part we used cast bushings with a wall 1 mm thick, 20, 30, 40 and 50 mm in diameter, with and without flange collars.

Figure 34 shows the principal forms of cast bushings used.
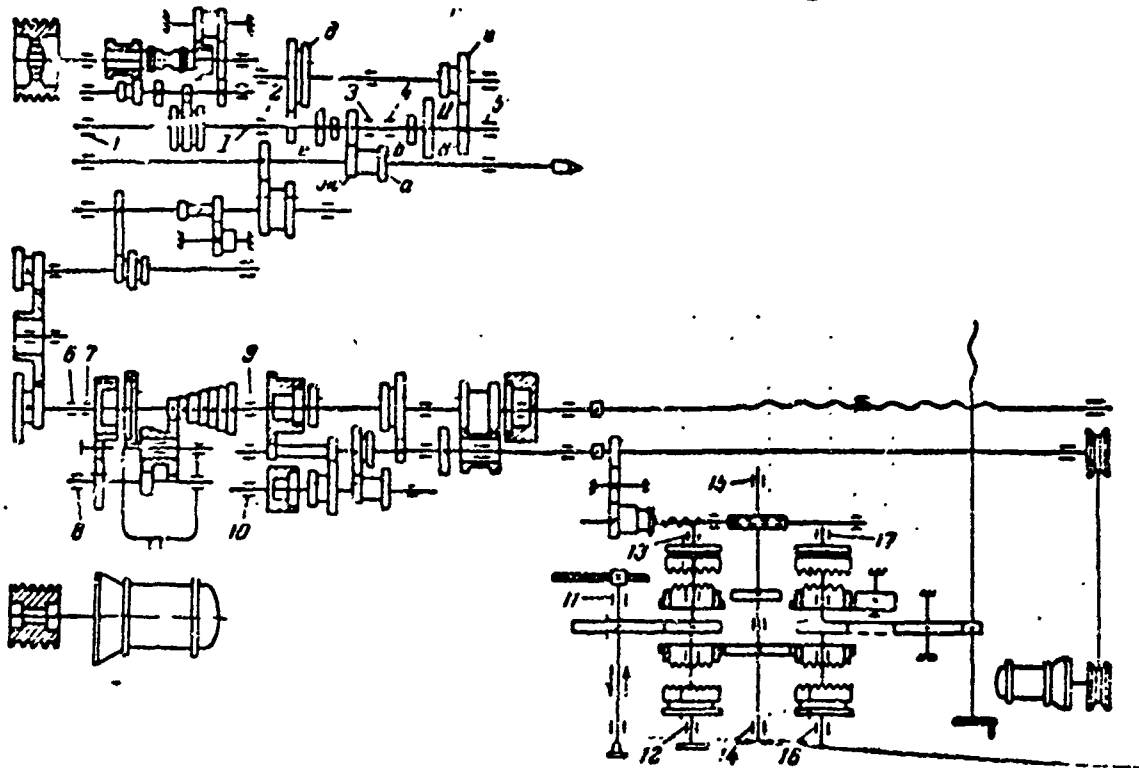

Fig. 35. Schematic diagram of machine-tool 1K62:
1 - 17 - sites of installation of capron bushings.

The installation of thin-walled bushings instead of roller and ball bearings made it necessary to build intermediate clips of Cu15-32 cast iron, pressed into the body, and bushings of St.45, fitted on existing shaft collars.

The surface of the intermediate bushings in contact with the capron bushings was ground down to ∇9-10.

The capron bushings were not machined.

Figure 35 is a diagram of the 1K62 machine, on which the numbers 1-17 indicate the sites of installation of the capron bushings. To measure the temperatures, the hot junctions of thermocouples of copper and constantan wire 0.12 mm in diameter were cemented into bushings 1, 3, 4, 5, 6, 8, 13, 15, 17 at a distance of about 0.8 mm from the friction surface. To protect the thermocouples against damage, they

were encased in polyvinyl chloride tubes 1 mm in diameter. The cold junctions, after the installation of the bushings in the machine, were attached to the blocks of current carriers whose temperature was measured by a thermometer.

The reservoirs of the front mandrel, the feed box and the apron, were filled with oil to the "oil level" mark.
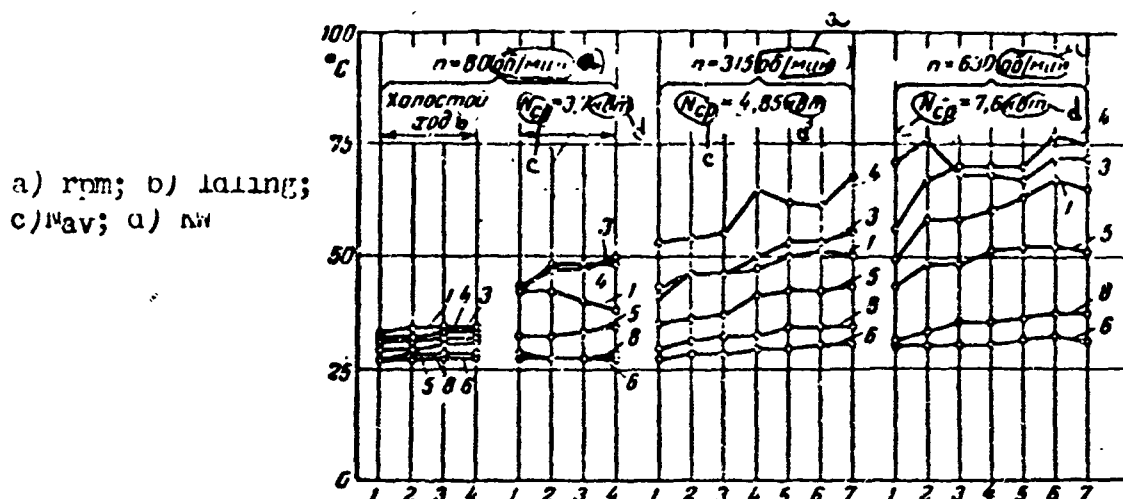
a) rpm; b) idling;
c)M_{av}; a) kw

Fir. 36. Temperature of bushings installed in 1h6? machine tool (cf. rig. 35) vs. load and number of loading cycles. The numbers of the curves correspond to the numbers of the bushings on the machine,

Industrial oil "20" was used. It had first been used in the normal operation of the machine for a month. Special oil chamfers were provided on the collar flanges of the intermediate bushings, and grooves were provided on the capron bushings, for lubrication in the working zones of the bearings.

The mechanisms of the machine were loading by turning an ingot.

The rpm of the spindle, shafts I and II of the speed box, the sliding speed of these shafts in the bushings, the torques on the spindle and the power consumed in cutting, are given in Table 12.

The average torques and the average power consumed in cutting were determined by calculation. Their actual values did not differ from those indicated by over ± 5%.

Table 12

Parameters	Regimes			
	1	2	3	4
Speed of spindle n_{sp}, rpm	80	80	315	630
Speed of shaft I, n_I, rpm	630	630	630	1260
Speed of shaft II, n_{II}, rpm	160	160	630	1260
Sliding speed on collar of shaft I, v_I, m/sec	1.65	1.65	1.65	3.30
Sliding speed on collar of shaft II, v_{II}, m/sec	0.42	0.42	1.65	3.30
Average torque of spindle M_{av}, kg/cm	0	4450	1500	1175
Average cutting power, N_{cut}, KW	0	3.7	4.85	7.6

The tests were run with closed gear train. The spindle speed of 630 rpm in the fourth regime was selected because only in this case was it possible to apply maximum load to all the test bearings of the speed box at maximum speed of shafts I and II rotating in them.

Indeed, at $n_{sp} = 630$ rpm, the speed of shaft II will be

$$n_{II} = 630 \cdot \frac{Z_a}{Z_0} = 630 \frac{54}{27} = 1260 \text{ rpm.}$$

Here $n_I = n_{II}$, since the transmission included two pairs of gears of ratio Z_b / Z_r and Z_A / Z_e having 45 teeth and a total gear ratio of unity.

At $n_{sp} = 2000$ rpm, shaft I is actually turning at the same speed as in the first case. It is connected with the spindle through a pair of gears with 43 and 65 ($Z_I + Z_A$) teeth respectively. But shaft II does not receive the load from the cutting force, while the conditions for the operation of the cutter with the machine running at full power at this speed are found to be less favorable.

The tests were run in cycle operation of the machine. One cycle included continuous operation at a load above indicated on one of the regimes for 10 min with a 4 min break. Under the severest conditions (3-4), the load was applied for 7 cycles (Fig. 36).

During the test period adopted, the temperature was held approximately constant.

Operation in the fourth regime was run at full power. Here the heating of the capron bushings of the speed box operating under the severest conditions did not exceed 78°C even for a short time. Bushing 5, installed in the front wall of the speed box was heated to not over 54°C. Bushing 6 and 8 of the feed box did not go over 37°C, and bushings 11, 13 and 17 of the apron (not shown in Fig. 35) did not exceed 26°C. The room temperature was 22-24°C. Thus, even under maximum load conditions, the heating of the most stressed of the operating bushings of the speed box did not exceed 80°C.

According to the data of our experiments, this temperature causes no decline in the wear resistance of capron in lubricated friction. Its antifriction properties remain sufficiently high.

Thus the results of our study of the maximum temperature of bearings reached under service conditions of a 1K62 machine tool indicates that the conditions of operation of capron bushings installed in the machine assure the effective utilization of capron as a bearing material.

It is advisable, however, to estimate the maximum temperatures to be attained only when one is sure that during prolonged operation there will be no substantial worsening of the operating conditions of the bearings, and no decrease in the lubricant feed as a result of the clogging of the lubricating grooves by the products of wear, etc.

CHAPTER VII

ANALYSIS OF PROBLEMS CONNECTED WITH THE MECHANISM OF FRICTION

Our work has shown that the principal relationships of the friction of a
polyamide-steel pair are determined by the molecular interaction between the contact
surface and by the character of their variation with temperature.

Boyers, Clinton, Zisman, as well as Moore, have suggested that the friction of
polyamide may be determined by molecular interaction, but they have performed no
investigations to verify this hypothesis.

G. M. Bartenev assigned primary importance to molecular influence in the
friction of polymer against smooth surfaces, and bases his conclusions mainly on
the results of studies of rubber. But the principal laws found by Bartenev in the
molecular-kinetic theory of rubber friction hav. not been confirmed for the friction
of polyamides.

Indeed, the distinctive feature of the process of friction described by the molecular-kinetic theories is a decline in the coefficient of friction with increasing temperature, and an increase in the coefficient of friction with increasing sliding speeds in the range of low speeds.

Experiments have shown that the opposite relationships hold for polyamides.

Since studies of the effect of load on the friction of polyamides have been performed for a varying area of actual contact, and in most experiments the physicochemical properties of the surface layers of the polymer have varied on account of the variation of the temperature, the results obtained give no grounds for a judgment as to the degree to which the molecular theory developed by B. V. Deryagin for hard bodies is applicable to the friction of polyamides.

On the whole, the results of the study are in agreement with the treatment of the process of friction given by the molecular-mechanical theory of I.V. Kragel'skiy, according to which friction has a dual, molecular-mechanical nature. Divergence occurs inasmuch as this theory proposes that the variation of the frictional force with the regime is due to the change in the mechanical properties of the surface layers of the frictional bodies.

The existence of a correlation between the frictional and mechanical properties is likewise assumed by the adhesion theory. Experiments have shown that there is no such correlation in the case of the polyamides.

Thus the primary difference in the behavior of the polyamides from the fundamental propositions of the molecular-mechanical and adhesion theories of friction, whose correctness has been many times confirmed by investigators on many materials, reduces down to the fact that, in the polyamide-steel pair, molecular interaction between the contact surfaces determines the character of the basic relationships of friction, and is itself of independent significance. This fact must be taken into account by a theory of friction that applies to polyamides as well.

The study of the physicochemical aspects of the mechanism of friction of polyamides is a separate problem.

On the basis of analysis of the results obtained, and of the literature data on questions of the structure of polymers, however, it seems to us that the peculiar character of the variation of the coefficient of friction of polyamides with temperature may be explained by the presence of atoms capable of forming hydrogen bonds in their molecular chains.

The structure of polyamides is irregular, and the arrangement of their molecular chains in the amorphous zones is disordered, so that not all the -NH and -CO groups of adjacent molecules are linked by hydrogen bonds.

This is responsible for the possibility of the formation of hydrogen bonds between the -NH groups on the friction surface and the oxygen of the oxide film of the opposite body.

A rise in temperature makes it possible, on account of the increase in the energy of thermal motion of the units of the molecules and the facilitated rotation of parts of the molecules about the C-C bonds of the methylene regions, for new -NH groups, which previously had been hindered from such interaction by the greater rigidity of the molecular framework, now to approach the oxygen atoms of the oxide film.

The number of -NH groups coming into instantaneous interaction with the oxygen of the oxides of the opposite body can also be increased by the rising temperature, which intensifies the scission of the intermolecular hydrogen bonds of the -CONH groups of the polyamide.

Presumably this increase is likewise favored by the multiple mechanical action of the opposite body.

The increase in the number of free-NH groups on the friction surface of the polyamides with rising temperature also leads to a relative increase in the molecular activity of the friction surface of polyamides as compared with that of other polymers.

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In this connection the following reasoning is of interest.

The saturation of dried polyamides with water encourages a decrease in its hardness by a factor of over three. On friction this should be manifested in an approximately proportional increase of the area of actual contact.

If constant activity of the molecular interaction between the friction surfaces is maintained, this in turn should be manifested in a corresponding increase in the frictional force (by a factor of about 3), since it has been established that the molecular component of the fri .onal force of a polyamide is the predominant factor. Experiments have shown, however, that the coefficient of friction of water-saturated polyamide increases by no more than 20%.

Since, in spite of the substantial increase in the area of actual contact, there is only a slight increase in the coefficient of friction, there are grounds for considering that the activity of molecular interaction between frictional contact surfaces decreases with the absorption of moisture by the polyamide.

This is apparently connected with the fact that the polar molecules of water diffuses in the space between the molecules of polymer and, interacting with the CO and NH groups, block them and thus decrease the number of active complexes able to interact with the surface of the opposite body. This may be an additional proof of the special role of the NH and CO groups in the formation of the frictional force of polyamide.

Thus it may be postulated that the behavior of polyamides during friction, and in particular the increase in friction with increasing temperature, is due primarily:

(1) to the presence, in the structure of the polyamide, of free polar groups and hydrogen atoms capable of forming hydrogen bonds;

(2) to the growth of the area of actual contact on account of the softening of the polyamides with rising temperature.

But the fundamental differences between the behavior of polyamides and other polymers during friction are connected primarily with the peculiarities of their structure, chemical composition, and polymeric constitution.

The pronounced influence of chemical composition and polymeric constitution on frictional behavior permits us to note that it is desirable for the composition of antifriction organic polymers to have one feature in common; one of the requirements should be the absence, or minimum number, of groups of atoms that can actively interact with the surface of the opposite body (provided sufficiently high mechanical properties are also maintained).

Based on our work, the following remarks on the application of polyamides may be made.

Since it has been established that the principal factors determining the friction of a polyamide under the operating conditions of a bearing material are the molecular interaction between the friction surfaces and the temperature, the major effort in the work of decreasing friction and increasing the serviceability of bearings of polyamide should be directed toward diminishing molecular interaction between the surfaces of polyamide and steel and preventing a rise in temperature.

The following methods of decreasing molecular interaction may be noted.

1. Introduction into the friction zone of substances that prevent molecular interaction. Experiments have shown the effectiveness of incorporating polar additives in the oil. The action of these additives is manifested primarily in preventing a rise in the coefficient of friction with rising temperature.

2. Introduction into the composition of the polyamide of substances decreasing the activity of molecular interaction. The fillers now employed, molybdenum disulfide and graphite, act in this direction.

It will probably be possible to select other substances exerting an action based on interaction with the free polar groups, especially groups that can form hydrogen bonds with the oxide film on the steel shaft, and on blocking such groups and preventing them, to the maximum possible extent, from interacting with the surface of the opposite body.

As for the methods of lowering bearing temperatures, these are quite generally known.

Conclusions

1. The major factors determining the friction of polyamides on steel with a mixed boundary lubrication or without lubrication are: molecular interaction between the friction surfaces, and temperature.

In this connection the major efforts to improve the antifrictional properties of polyamides and improve the serviceability of polyamide bearings should be directed toward the maximum prevention of molecular interaction and toward lowering the temperature of friction units.

2. The main differences in the behavior of polyamides from the behavior of other polymers in friction are connected with the peculiarities of their chemical composition and structure, with the presence of polar groups in the structure of the polyamides, and with the peculiarities in the character of variation of molecular interaction with the surface of the opposite body with varying friction conditions.

3. One of the requirements that must be met by the composition of a high-grade antifrictional polymeric material operating with insufficient lubrication should be the requirement of the absence or minimum content of chemical groups actively interacting with the surface of the opposite body (while retaining sufficiently high mechanical properties of the polymers).

4. The addition of polar-active substances to the mineral oils is an effective means of lowering friction and increasing the serviceability of capron bearings.

5. Heat treatment at 20-30°C below the melting point does not substantially and permanently increase hardness; this increase disappears after absorption of moisture. The temporary change in the hardness of polyamides after heat treatment is due mainly to the removal of moisture, which exerts a plasticizing action.

6. An evaluation of the temperature level that can be reached under service conditions may be used as a criterion for judging the possibilities of application of a polyamide in a specific unit.

7. In spite of the fact that certain features of polyamides have an unfavorable effect on their antifriction properties, polyamides are good antifriction materials. Their use in friction units of various machines and mechanisms is entirely possible and advisable.

In particular, our study has shown that it is entirely possible to use capron, which is a polyamide, for the manufacture of bearings to operate in the principal mechanism of metal-cutting machine tools.

8. The test temperatures of friction for polyamides should be one of the principal forms of evaluating their antifriction properties; such tests should be run under conditions as close as possible to the service conditions of the anti-friction material with mixed boundary lubrication or without lubrication.

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Footnotes

(p. 35) *The water temperature was 13-14°C.

(p. 69) *In tests performed at the Experimental Research Institute for Machine
         Tools, with the participation of Yu.A. Bykov and M.V. Merkulova.

(p. 70) *The shafts were of steel 45, heat treated to hardness NRS 37-40, surface
         finish corresponding to ∇ 10.

(p. 79) *The tests were performed in the Department of Metallurgy and Materials,
         ENIMS, and at the Stankokonstruktsiya Plant.